

Evaluation of Power Supplies in Solar Applications with Special Focus on Micro Inverters

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<p>Solar power together with wind, is predicted to dominate the energy sector in the future. This is needed in order to stop the global warming and eliminate the usage of fossil fuels. During last years the cost of solar system has decreased significantly, which enables solar power to become more common. Advantages of solar power is amongst other things that it is available all around the world and it is an incessant energy source. However disadvantages are the low efficiency of solar panels and their global enervating manufacturing process.</p> <p>One of the most important part of a solar system is an inverter, which inverts direct current (DC) to alternating current (AC). Further tasks, which are fulfilled by inverter, are for example maximum power point tracking (MPPT), boosting the voltage to needed level, protection and reactive power compensation. One main part of inverter are semiconductor components, which are used as switches.</p> <p>The purpose of this thesis was to evaluate the current situation of the solar inverter industry. Target was to evaluate the current market of solar inverters and to find out, which topologies and semiconductor components are commonly used. Final goal was to tear down few units, reverse engineer them and replace used switches with superjunction MOSFETs from the selection of Infineon Technologies.</p> <p>This thesis consists of a literature review, which follows the introduction. There the function of inverter, different inverter types and commonly used topologies are introduced. Second part of the thesis is a tear down -section, where four micro inverters were opened and reverse engineered. Before conclusion, measurements are represented.</p>		
Keywords: Solar Power, Solar Inverter, Micro Inverter, Semiconductor components		

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<p>Aurinkoenergian on yhdessä tuulen kanssa ennustettu hallitsevan energian tuotantoa tulevaisuudessa. Tämä on välttämätöntä, jotta ilmastonmuutos saataisiin pysäytettyä ja fossiilisten polttoaineiden käyttö lopetettua. Viime vuosina aurinkosähköjärjestelmien hinnat ovat laskeneet huomattavasti, minkä vuoksi aurinkoenergia on yleistynyt. Auringosta saatavan energian hyötyjä ovat muun muassa se, että sitä on saatavilla kaikkialla maailmassa ja se on loppumaton energianlähde. Toisaalta aurinkopanelien heikko hyötysuhde sekä valmistusprosessin ympäristökuormitus ovat aurinkoenergiaan liittyviä haasteita.</p> <p>Tasavirtaa vaihtovirraksi muuntava invertteri on yksi aurinkosähköjärjestelmän tärkeimmistä laitteista. Lisäksi invertterin tehtäviä ovat muun muassa maksimitehopisteen mittaaminen, jännitteen korottaminen, suojaus sekä loistehon kompensointi. Eräs tärkeä osa invertteriä ovat puolijohdekomponenteista valmistetut kytkimet. Tämän diplomityön tarkoituksena oli arvioida aurinkoinverttereiden tämän hetkinen markkinatilanne. Kirjallisuuskatsauksen lisäksi muutama invertteri purettiin osiin ja tutkittiin, mitä topologioita ja puolijohdekomponentteja niissä on käytetty. Lopuksi suoritettiin mittauksia ja selvitettiin, päästäänkö Infineonin valmistamilla superjunction-puolijohdekomponenteilla parempaan hyötysuhteeseen, alkuperäiseen kytkimiin verrattuna.</p> <p>Johdannon jälkeen seuraa kirjallisuuskatsaus, jossa eri topologioita ja invertterityyppejä on esitetty. Kolmas osa tätä työtä käsittelee osiin purettuja inverttereitä, jonka jälkeen ennen johtopäätöksiä, mittaustulokset esitetään.</p>		
Avainsanat: Aurinkoenergia, Invertteri, Mikroinvertteri, Puolijohdekomponentti		

Preface

Now, when this thesis is finished, it is time for acknowledgements. Thank you Infineon Technologies AG and PMM for enabling to write my thesis in wonderful Villach, about a very interesting topic. Thank you Damijan Zupancic for committed supervision during my thesis and Julia Jaendl for making this half a year possible. Thanks also to all colleagues who I got to meet during my time in Infineon, I learned something from all of you.

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Symbols and abbreviations

Symbols

$^{\circ}\text{C}$	Degree Celsius
Hz	Hertz
k	kilo, 10^3
I	Current
I_D	Drain Current
I_{in}	Input Current
I_{out}	Output Current
j	Imaginary unit
m	Milli
min	Minute
n	nano, 10^{-9}
P	Active power
P_{in}	Input Power
P_{cond}	Conduction losses
P_{out}	Output Power
Q	Reactive Power
R	Resistance
$R_{DS(ON)}$	Drain-Source Resistance in On-State
$R_{DS(OFF)}$	Drain-Source Resistance in Off-State
$R_{GS(ON)}$	Gate-Source Resistance in On-State
s	Second
S	Complex Power
V	Voltage
V_{in}	Input Voltage
VA	Volt-Ampere
V_{DS}	Drain-Source Voltage
V_{GS}	Gate-Source Voltage
$V_{GS(TH)}$	Threshold Voltage
V_{GS}	Gate-Source Voltage
V_{MPP}	Peak Power Tracking Voltage
V_{out}	Output Voltage
W	Watt
€	Euro
η	Efficiency
Ω	Ohm

Operators

$\frac{d}{dt}$	Derivative with respect to variable t
$\cos(\phi)$	Cosinus of Angle ϕ

Abbreviations

AC	Alternating current
BoS	Balance of System
CEC	California Energy Commission
CM	Common Mode
CO_2	Carbon dioxide
CPU	Central Processing Unit
DC	Direct Current
DC/AC	Conversion from Direct Current to Alternating Current
DC/DC	Direct Current conversion
EMI	Electromagnetic Interference
ESR	Equivalent Series Resistance
EU	Europe
GaN	Gallium Nitride
IEEE	Institute of Electrical and Electronic Engineering
HV	High Voltage
IGBT	Insulated-Gate-Bipolar-Transistor
IGCT	Integrated Gate-Commutated Thyristor
IV-Curve	Current-Voltage Curve
LV	Low Voltage
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MOV	Metal Oxide Varistor
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MTTF	Mean Time to Failure
MV	Medium Voltage
NMOSFET	N-Channel MOSFET
PCB	Printed Circuit Board
PF	Power Factor
PFC	Power Factor Correction
PV	Photovoltaic
PWM	Pulse Width Modulation
S1	Upper Left Switch of the H-bridge
S2	Lower Left Switch of the H-bridge
S3	Lower Right Switch of the H-bridge
S4	Upper Right Switch of the H-bridge
SiC	Silicon Carbide
TH	Threshold
THD	Total Harmonic Distortion

1 Introduction

Global warming, scarcity of conventional energy sources, and an ever increasing demand of energy have put pressure on developing renewable energy sources. Challenge of this century is to figure out, how to meet energy demand without impacting the climate. Figure 1 shows how the share of energy, produced by renewable energy sources, is predicted be dominating in the future, already in year 2040.[1]

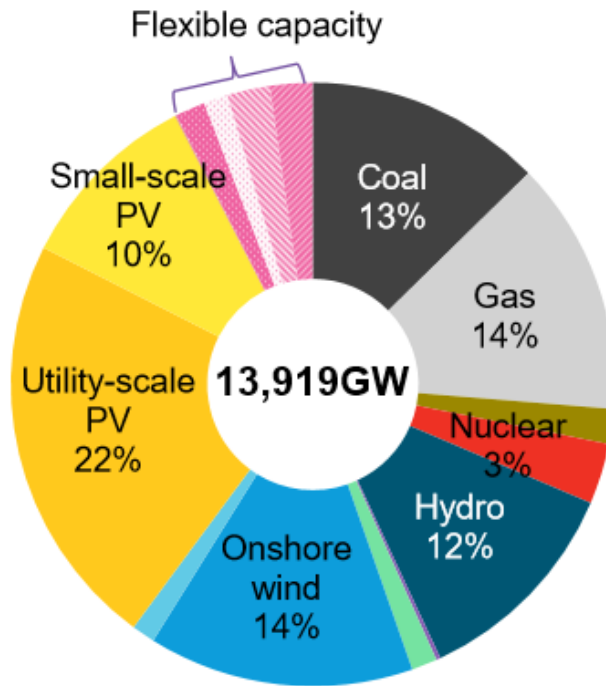


Figure 1: Amount of energy generated by solar power is forecasted to dominate in the year 2040. Also wind and hydro power are going to play a significant role in the future.[1]

Solar energy is predicted to be one of the dominating energy sources in the end of this century. Its advantages are its impossibility to deplete, pollution freedom, and availability all over the world. In addition it has no noise impact, solar panels do not require active maintenance, and expected lifetime of solar panels is long. On the other hand, disadvantages of solar power are its need to be stored, scarce and expensive building materials, and indirect environmental impact.[2] In this thesis photovoltaics (PV) as solar energy harvesting methods are discussed.

However, high penetration of distributed energy generation will cause challenges to today's grid, since current transmission network is mainly designed and built to distribute energy from centralized production, e.g fossil energy. Changing this infrastructure will be challenging, as the key challenges are voltage and frequency regulation and the fact that renewable energy is normally attached to low voltage network.[3][4]

Inverter is a central part of a solar energy system. Solar panels produce direct current (DC) that is converted by an inverter to alternative current (AC), which can be fed into the grid or used in a local load. An example of a local load is e.g household or an electric vehicle. In addition, inverters play a significant role in the grid management, such as active and reactive power and frequency regulation on the periphery of the power grid.[4][5]

Semiconductor components, which are used for example as switches, compose an important part of an inverter. Their purpose is to provide efficient, reliable, stable and clean energy conversion.[6]

The market for solar panel systems can be divided to three parts, which are residential, commercial, and utility sector[7]. This thesis focuses on the residential sector and especially on micro inverters, and additionally different inverter types are introduced.

Theoretical background, which is done as a literature review, follows introduction and there different inverter types, prospects, used topologies, grid regulations and semiconductor components are introduced. Theoretical background is followed by the practical part of the thesis, where inverter tear downs have been conducted and the results of efficiency measurements are presented. Last part of this thesis is conclusion.

2 Theoretical Background

This section provides the needed knowledge and background for this thesis.

2.1 Solar Panel System

Solar energy has lots of potential to become the dominating energy source in the future. Its volume has increased a lot during last decades.[8] Figure 2 shows, how the amount of global cumulative installations in wind and solar power has increased between years 2000 and 2016 and how the amount is predicted to develop until year 2021.[1] As the Figure 2 shows, wind power took off earlier than solar power, but due the massive price reduction, solar energy starts to be competitive.

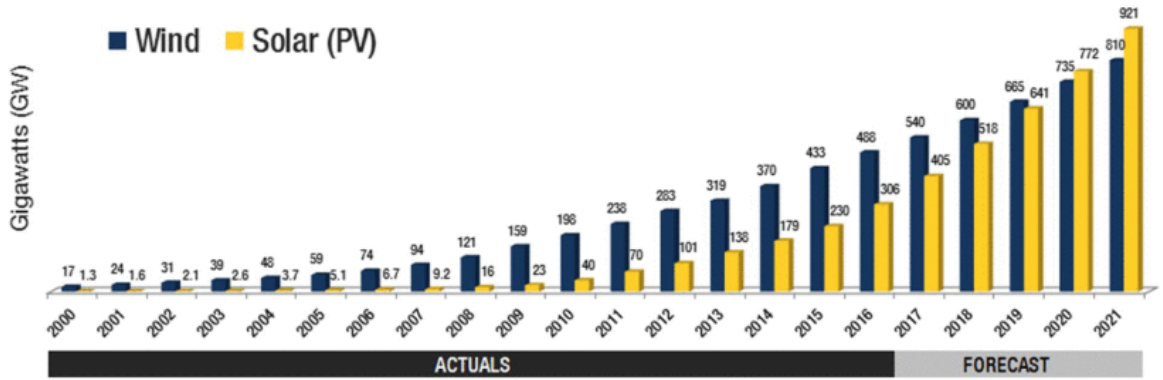


Figure 2: Global cumulative installations 2000-2016 and forecast until the year 2021 in wind and solar. Solar power is predicted to dominate in the future.[1]

Sun provides an inexhaustible and clean energy source as light and heat. The radiation of sun reaches the Earth annually 8000 times more compared to total energy consumption on the globe. During energy harvesting, day light is transformed to electric current in the semiconductor material of the solar cell. When the light hits the semiconductors, electrons start to move and this movement produces DC. Solar cells can be divided into two sections, which are multicrystalline and monocrystalline cells. First mentioned are blue and their efficiency is around 11-15 %. Monocrystalline panels are black and their efficiency is better, around 13-17 %, but due to manufacturing process, they are more expensive. Because of the price, multicrystalline panels are used more. Solar cells are connected to series and these series compose the solar panel.[9] Figure 3 illustrates the solar system.

As every energy source, also energy harvested by solar panels, has both advantages and disadvantages. Its advantages are for sure the pollution free energy and no carbon emissions. PV also converts sunlight directly into electricity. Panels do not have any mechanically moving parts, which requires significantly less maintenance compared to conventional power plants. In addition, solar panels are robust in varying weather conditions, solar energy is impossible to deplete and available all over the world. Also, the expected lifetime of solar panels is long and panels are available in multiple sizes and can be used for different applications.[2][10][11] In

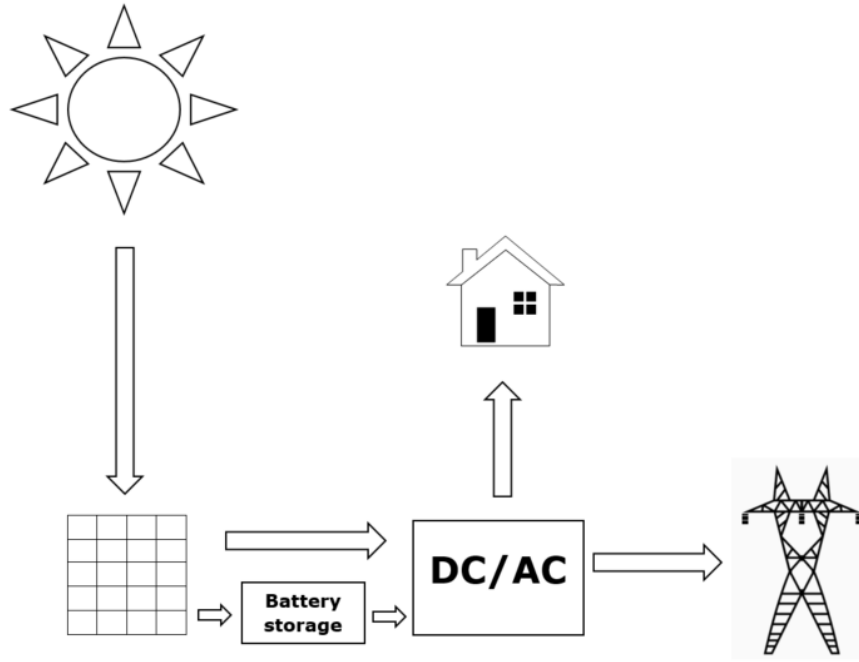


Figure 3: Simplified illustration of solar energy system. Energy, harvested by solar panels, can be either fed directly to the inverter, or be stored in a battery before.

addition, one major advantage of power produced by photovoltaics, is its simplicity. The process from sun shining to solar panels and until it is fed into utility, is almost only completely solid state.[4]

Disadvantages of solar panels are their high cost due to scarce and expensive building materials and the availability of solar power is limited to day time, which makes the energy storing necessary. In addition, manufacturing of solar panels burdens environment, so solar panels have indirect negative impact to climate warming, even though the produced energy itself is clean. Anyway, when considering the emissions, solar panel system compensates the emissions, produced due to manufacturing, in two years after the commissioning. One installed kW saves annually CO_2 emissions approximately 0.7-1.3 tons [9]. Also the energy efficiency of solar panels is comparatively low, around 15-20 % [12]. Energy efficiency of solar panels signifies the percentage of solar energy shining on the panels that is converted to usable electricity [13]. Panels also require cleaning, because dirt or dust on the panels decreases the conversion efficiency.[2][11][10]

Figures 4 and 5 represent an example of residential energy production. These Figures, mentioned before, show the output power of solar panels, which are installed on the roof of a detached house in Southern Austria. Panels are installed to the southern side of the house and their angle is fixed, so they do not follow the sun. 14.6 was a very sunny day, as also the Figure 4 shows. Panels starts to produce power immediately after the sunrise and the power increases when the sun rises more. Between 8am and 5pm the energy production is significant and after 5pm it starts to decrease. Some power is still produced until the sunset. Figure 5 shows, how a

cloud affects to power production. Output power of the panels drops almost 3 kW when a cloud appears in the afternoon.[14]

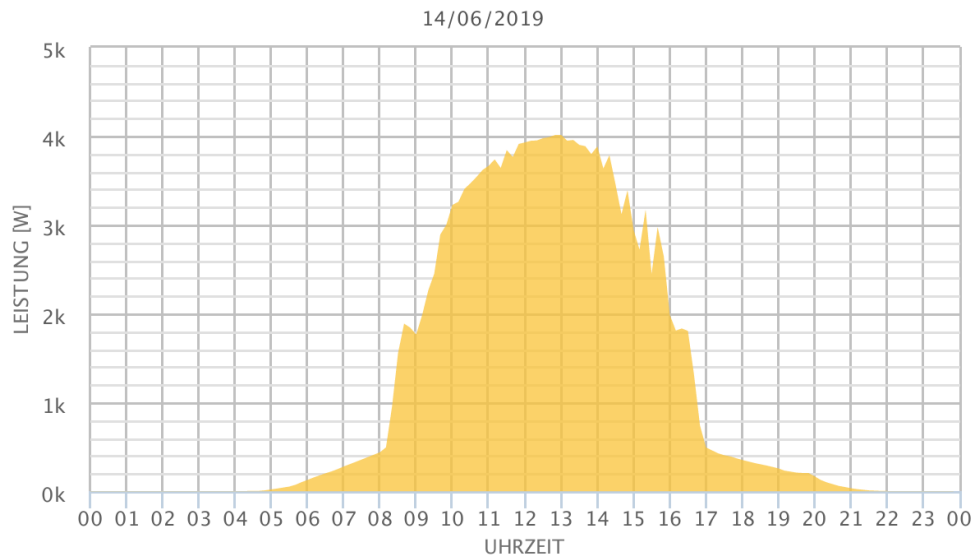


Figure 4: Data of output power of solar panels installed on the roof of a detached house in Southern Austria. 14.6.2019 was a very sunny day, which can be seen from the Figure. "Uhrzeit" stays for time and "Leistung" for power.[14]

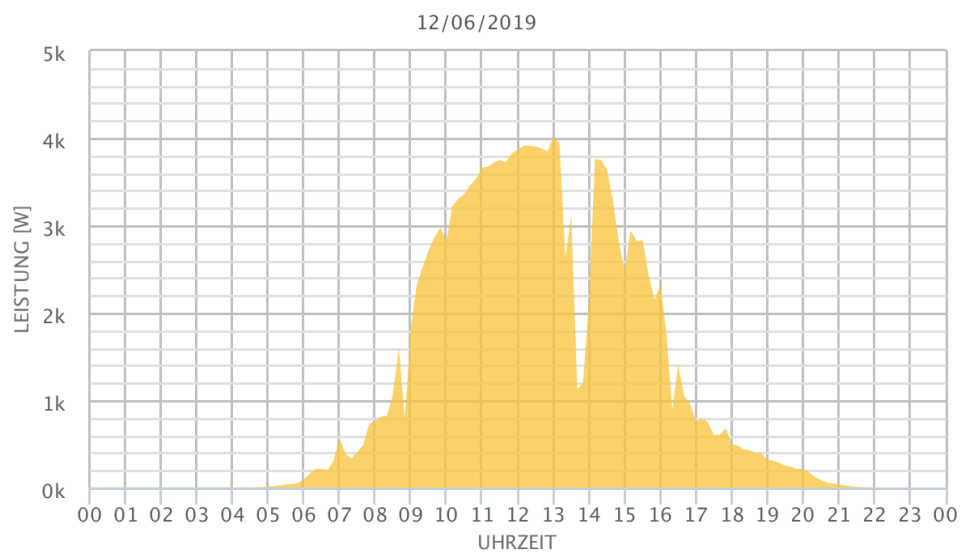


Figure 5: Data of output power of solar panels installed on the roof of a detached house in Southern Austria. 12.6.2019 was a quite sunny day, but as can be seen from the Figure, in the afternoon, between 1pm and 3pm, a cloud was shadowing the panels quite heavily. "Uhrzeit" stays for time and "Leistung" for power.[14]

Market for solar panel systems can be divided to three sections, listed in Table 1 [7]. Also common power range for each section is presented.

Table 1: One way to divide market for solar panel systems.

Section	$P_{installed}$ (W)
Residential	< 10 kW
Commercial	10-100 kW
Utility	> 100 kW

DC voltage, produced in one solar panel, is normally small and higher voltage levels are needed for the load. Voltage can be increased for example by boosting the voltage with DC/DC converters, or putting many panels to series. Inverter's voltage limitations in different temperatures determines the possible amount of panels in the input. The maximum amount of panels, that can be installed in series, is told in the datasheet of inverter.[4][15]

2.2 Inverter

Inverter has a central role in a solar energy system and it is also the most complex component between solar panels and the local load or utility.[4] It converts the DC voltage, produced in solar panels, to AC voltage. This AC voltage can be used in the local loads, like households or electric vehicles, or fed to the utility grid. In addition to inverting the DC, inverter must also be able to shape the current into sinusoidal waveform and boost the output voltage to the voltage level of the grid or local load.[4][5]

Both 1-phase and 3-phase solar inverters exist on the market and which one is used, depends for example on the application, country regulations and voltage levels of the end usage.[16]

Inverters can be divided to two groups, which are Grid-tied inverters and Stand-alone inverters. Grid-tied inverters are connected directly to the grid and in case there is surplus energy after feeding power to the household or another local load, the surplus energy can be fed to the grid. This is called net export. On the other hand, when the output power of the PV is adverse, the grid supplies the power difference to the household, so the local loads can run. In this case grid works as an infinite sized battery. This is called net import.[17][4][6]

Stand-alone inverters are connected to local loads via energy storage systems and feeding power to the grid is not possible. Where grid-tied inverter only needs one piece of electronics between solar arrays and grid, stand-alone inverters also need a DC/DC converter between arrays and battery. In addition in case of stand-alone inverter, it must include a built-in charger. Grid-tied inverter is an important unit in distribution systems, since it is the interface between renewable energy source and the utility. Since the importance of grid-tied inverters, focus of development is

currently on them. Figure 6 clarifies the difference between grid-tied and stand-alone inverters.[17][4][6]

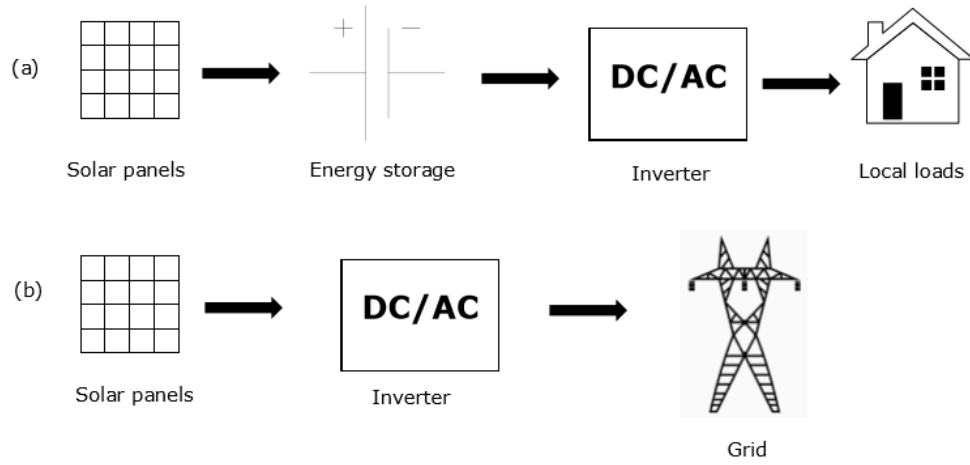


Figure 6: Simplified illustration of a) stand-alone and b) grid-tied inverter.

Some important inverter types are represented in Table 2. Also general approximate power levels, according to one scientific article [6], for each type are shown. Nevertheless power levels for inverters are so called grey area, since power usage levels are not so strict. All of these inverter types will be clarified more deeply in Sections 2.2.2- 2.2.6.

Table 2: Different inverter types with their approximate power levels.

Inverter type	Power level
Micro inverter	< 1 kW
String inverter	< 1-10 kW
Power optimizer	1-10 kW
Cascaded inverter	10-30 kW
Central inverter	> 30 kW

In addition for converting the DC voltage to AC, inverters have also an important role in grid management: amongst other things they have to be able to feed reactive power to utility grid and participate to frequency control.[5] A wider overview about grid requirements can be found later in the thesis, in Section 2.7.

2.2.1 Tasks of Inverters

Below are listed the main features, that a solar inverter should fulfill [16][5][17][18]:

- Efficient inversion
- Boosting DC voltage
- Maximum Power Point Tracking (MPPT)
- High reliability
- Protection
- Low in Electro Magnetic Interference (EMI) and in Total Harmonic Distortion (THD)
- Small in weight and size
- Low in cost
- Easy module integration
- Safety
- Support for usage
- Weatherproofness
- Meeting the lifetime of PV panel
- Enabling the system expansion
- Integration
- Packaging

Inversion is made with power semiconductor components, which are used as switches. In conventional full-bridge topology, and in its derivatives, these switches basically flip DC voltage back and forth, which produces AC voltage. Details about topologies and semiconductor components can be found later in this thesis. Figures 7 and 8 explain the use of four switches, which is one of the simplest configuration, to produce AC voltage in a single-phase inverter.[4] Switches, marked with S1, S2, S3 and S4, in Figures 7 and 8 are simplified and for example parasitic components are not represented. These switches are semiconductor components, normally; MOSFETs, thyristors or IGBTs. These components are represented in detail in Section 2.8. What should be observed here, is that numbering of switches is done similarly in the whole thesis, than in Figures 7 and 8.

Switching diagonal switches S1 and S3, and S2 and S4, alternately, produces AC waveform, which is rectangular. This is called pulse width modulation (PWM). However, output voltage should be sinusoidal so it can be fed into the grid. Therefore,

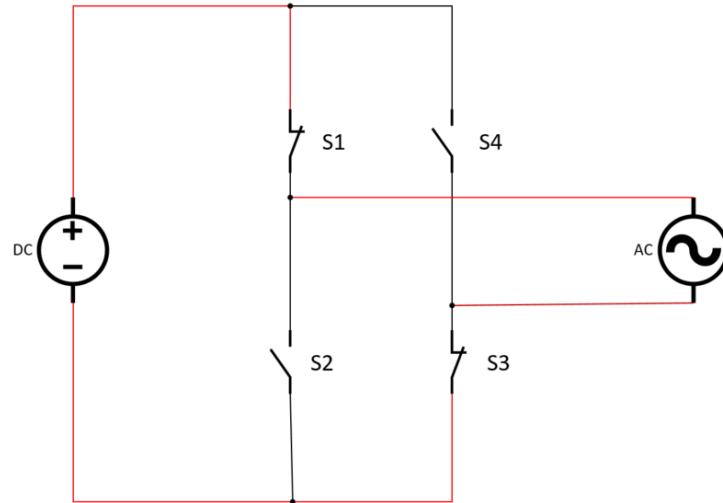


Figure 7: Red line shows how current is flowing in full-bridge topology when switches S1 and S3 are closed and switches S2 and S4 are open. This is how the positive half cycle of sinusoidal wave is produced.

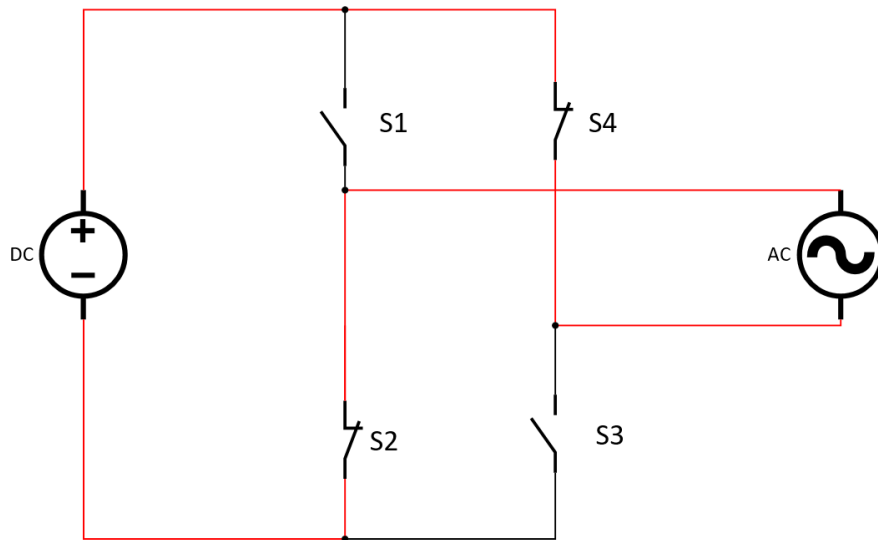


Figure 8: Red line shows how current is flowing in full-bridge topology when switches S2 and S4 are closed and switches S1 and S3 are open. This is how the negative half cycle of sinusoidal wave is produced.

after inversion, voltage is smoothened with magnetic components, more specified with inductors, capacitors and transformers, in case inverter is transformer-based.[4]

Converting DC to AC is known as inversion and it naturally is one of the main purposes of an inverter. Inversion is needed because our electrical power infrastructure is based on AC power. One reason amongst other things to AC-based grid is that AC can be stepped up and down with minimal amount of material.[4]

Before inversion, input voltage of inverter is boosted, in case the output power of solar panels is low. This is important, since output voltage of an inverter must be on certain level, so it can be fed to the utility or to household. This is also explained in Section 2.2. Maximum Power Point Tracking is a special feature of solar inverter and it will be explained in detail in Section 2.5.2.

Solar inverters must fulfill the security standards and have an integrated protection system against short circuits, over currents, over voltages and over heating. The solar system must be disconnected from the grid, when the grid has a failure or works outside of the limits, i.e. in over or under voltages or frequency. Also isolated operation and realization of shortages to ground are required. Nevertheless the solar system should not be disconnected from the grid immediately when the voltage in the grid starts to drop: it should first try to support the grid by feeding reactive power to it. If the voltage in the grid do not stabilize in few seconds, the solar system should be disconnected. In addition, solar inverters must be safe for end user to use and their function must be reliable in changing weather conditions all around the year.[5][17]

Solar inverters should also provide support for the end user: How many panels are needed for the system and what is the maximum amount of panels, that can be attached in series, so the inverter still works. Also naturally the possible voltage range, maximum current, power range, range for MPPT, operating temperature etc. has to be told. These things are normally provided in the datasheet of the inverter.[?] Additionally to datasheet, separate user manual is provided. It tells all required information, that is needed for connecting the inverter to solar system. Some examples of needed and provided information are: electrical connections, safe usage, installation and proper mounting, and how to commission and decommission the device. Inverters have normally a LED-light, which indicates if the commissioning worked out and if not, certain signals tells, what went wrong. All of this information is provided in the user manual of the inverter.[18]

Inverter produces Electro Magnetic Interference (EMI) and Total Harmonic Distortion (THD) to the grid. EMI means the phenomenon, where two different electromagnetic fields interferes with each others. As result, both fields have distortion, even though they would function in different frequencies. This disturbance is in radio frequency spectrum and is easily picked up by any conductor. THD-value tells, how much noise or distortion the system has in its output. Values for THD are between zero and one for each tested frequency and the closer the value is to zero, the less harmonic distortion the system has. THD is the energy, which is unrelated to input, divided by the total energy. For example used modulation topology, dead time, voltage drops in the switches of inverter, filtering and voltage of the intermediate circuit affects to the magnitude of THD.[19][20]

Lifetime of solar panels with present technology is around 20 to 25 years, whereas solar inverters reach normally 10 to 20 years. One common limitation in the lifetime of inverters is used electrolytic capacitors. More about this can be found from Section 3. The more popular solar energy gets, the more attention has to paid also to increasing the lifetime of inverters. Lifetime improvement can be done for example by redesigning the inverters with capacitors or advanced power semiconductor devices.

To achieve an efficient design, degradation of components should be taken into account when estimating the lifetime of inverters.[8]

Solar inverters must also enable the system expansion. This means, that when end user wants to meter the production or consumption, add smart controlling to the system and control it for example with mobile phone, use batteries for storage or charge an electric vehicle with the solar system, it system should make this possible.[16]

In the Sections 2.2.2- 2.2.6 the most common inverter types are introduced.

2.2.2 Micro Inverter

Even though first micro inverters were discovered already in the 90's, lots of research has recently made on the field of power electronics concerning micro inverters[10]. Micro inverters can either be integrated to solar panels or then installed separately to the roof. When they are integrated, they are bolted to the back of the panel, so they compose one single unit. Separate micro inverter units, then again, are located on the rails close to micro inverters. Integrated inverters are faster to install and less cables are needed, but they also are more expensive. Also the panels that can be used with integrated micro inverters, are limited.[21]

Micro inverters are isolated from each others. Integration enables solar panels to work as plug and play devices. Each micro inverter is fed by the solar panel with output power normally around 300 W [22] and inverter is connected straight to the grid or local load. Micro inverter is presented in Figure 9.[10][23][17][24]

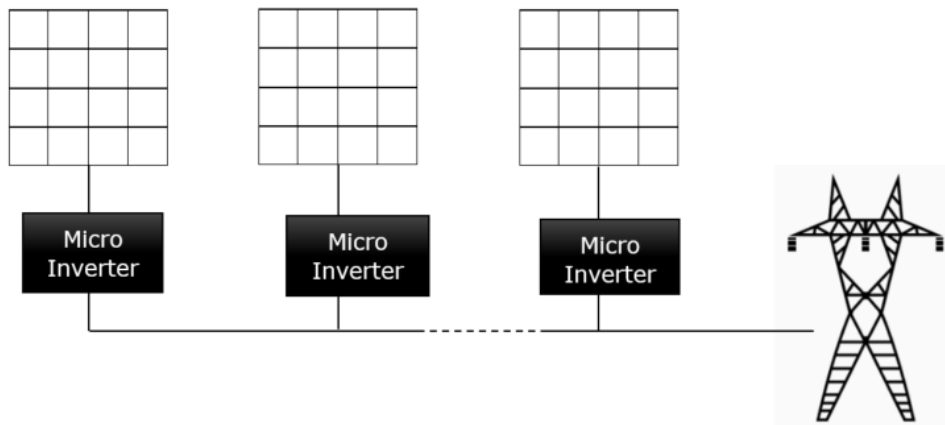


Figure 9: When every panel has an independent inverter, this inverter is called micro inverter.

Micro inverters are fault tolerant and MPP is tracked to every panel individually. This optimizes the output power of the system, since there occurs no power mismatching: even though part of the panels would be completely shaded, others would work perfectly. The effect of shading by a cloud can be seen in Figure 5 presented in

Section 2.1 in this thesis. In addition, monitoring in panel level is offered. Micro inverters are normally installed directly to the roof due to their modular nature, so cabling is minimized, and installing and maintenance is simple and cost efficient. In addition, micro inverters are robust with changing weather conditions.[10][23][17][24]

One implementation for micro inverter is a multi-channel, i.e. dual-module micro inverter, which has two input channels. It has individual MPP-tracking and boost-function for each panel, but housing is combined. Nowadays also micro inverters with more than two channels, exist on the market. A dual-channel micro inverter is presented in Figure 10.[15]

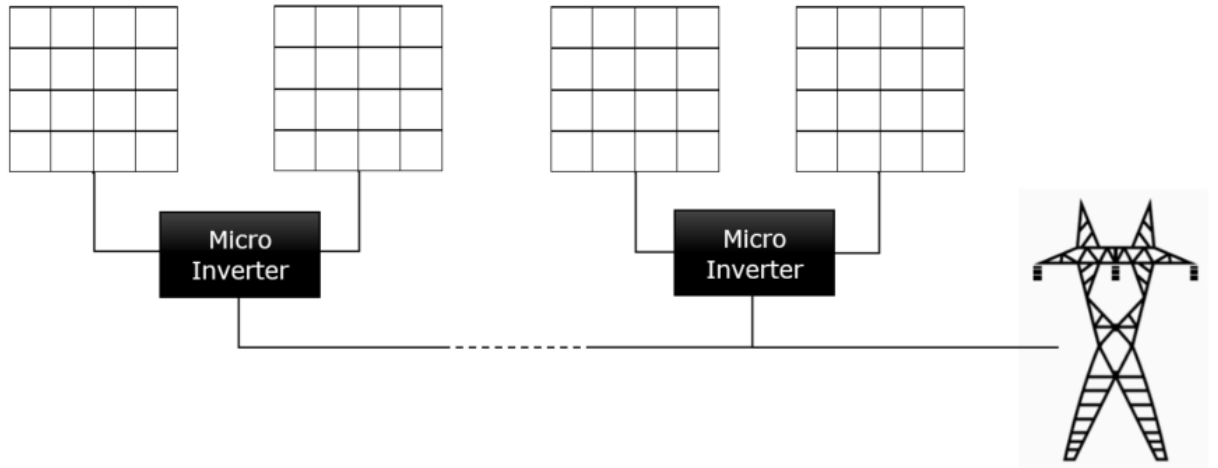


Figure 10: Multi-channel i.e. dual-module micro inverter.

System requirements for micro inverters are higher compared to conventional applications, which are normally installed inside or to a sheltered location. Due to the fact, that micro inverters are installed straightly to the roof, they must be able to handle varying temperatures (-40°C to even 80°C) and they must be waterproof. Major disadvantage of these requirements is their high cost, since lots of devices are needed, compared to not-integrated and to sheltered inverters. However, installation costs cover a significant part of total costs in residential installations and therefore in residential area micro inverters make sense. In addition, micro inverters suffer from poor conversion efficiency, since output voltage of one panel is very low compared to voltage needed in the grid or local load ($50\text{ V} \rightarrow 400\text{ V}$). Also ability to control micro inverters remotely is desirable, since they are located on the roof. [10][23][17][24]

Micro inverter with multiple channels is currently popular. It is like dual-module micro inverter presented in Figure 10, but with more than two input channels. Also this type of micro inverter has individual input channels, which are not connected. Each of these channels have an embedded and isolated MPPT. Multi-channel inverter is a cost effective solution and provides fast installation, low logistics and it is easy to maintain, since instead of many devices there is only one.[10][23][17][24]

2.2.3 String Inverter

String inverter is the most common inverter type in residential installations, where inverters are installed to series with n-amount of solar panels. This method is simple and perfect in theory, because it is so well tested. String inverters are high in efficiency, robust and low in cost. They are also well supported and have remote monitoring capabilities. String inverter is shown in Figure 11.[17][23][10]

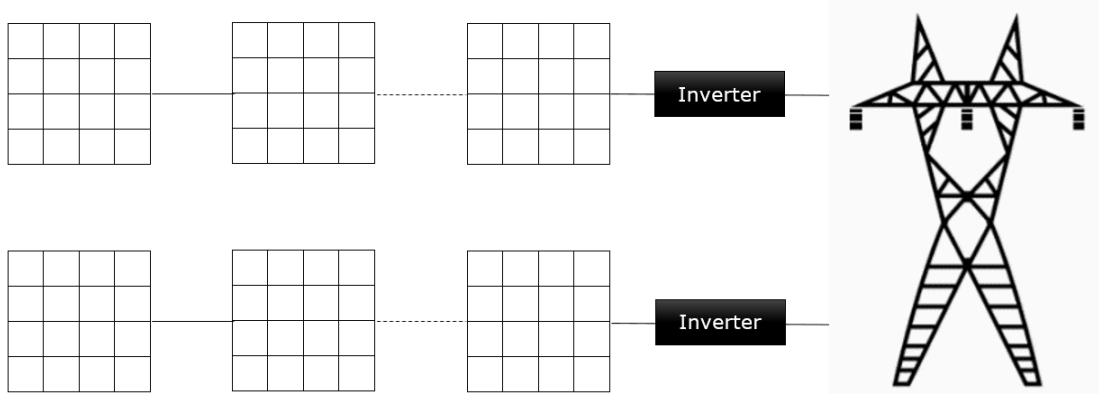


Figure 11: String inverter is installed in series with n-amount of solar panels.

However, one string has only one MPPT, which leads easily to mismatching with the IV-curve. IV-curve is explained in detail on Section 2.5.2. It is unlikely that the current flows through the string at the MPP of every panel. This naturally lowers the system efficiency, because the MPPT process has lots of losses and not all the potential power from solar panel is utilized. In addition to the lack of individual MPPT, string inverters do not have panel level monitoring either. Compared to micro inverters, voltage levels in string inverters are much higher, which increases the potential safety hazards. Also disconnecting high DC causes arcing.[17][23][10]

Because micro and string inverters are often used in similar conditions, for example in residential usage, comparing these two is necessary. Micro inverters offer better economical and physical scalability and they save space compared to string inverter. In addition, micro inverters are less noisy, produce less heat, and because of individual MPPT, they offer a highly efficient PV system. Micro inverters are low in cost because of the decrease in Balance of System (BoS). With BoS, all the components, irrespective of PV panels, are meant. These components are for example wiring, switches, inverter(s), batteries, chargers and a mounting system[25]. Even though the initial investment is high, in the long run produced power is higher than in string inverters, which leads to lower total cost. Micro inverters also increase the reliability of the system, since the installation is simple and reduce the risk of arcing, because standard AC wiring is used. In micro inverters also DC cabling is minimized, because of integration. Some researches claim micro inverters to be the best choice for building integrated solar panels.[17][23][10][25]

On the other hand string inverters are lower in cost (€/W) compared to micro

inverters. Micro inverters are exposed to extreme weather conditions, while located on the roof. Humidity, high peaks and variation in temperatures and lighting reduces the mean time to failure (MTTF). Also in case of failure, micro inverters can be difficult to fix. However, in case of failure in a string inverter, the whole string of panels is inoperative as long as the fault is fixed, whereas if a failure occurs in a micro inverter, only one panel is out of service.[10]

2.2.4 Central Inverter

Central inverters are used in large scale applications in commercial and industrial sections. Examples of these applications are large arrays on the roofs, industrial facilities or field installations. Central inverter, shown in Figure 12, reminds otherwise enormous string inverter, only strings are first connected to a common combiner box which then feeds the DC power to central inverter. Advantages of central inverters are their high efficiency, low capital price per watt and comparatively easy installation. Also fewer component connections are required.[23]

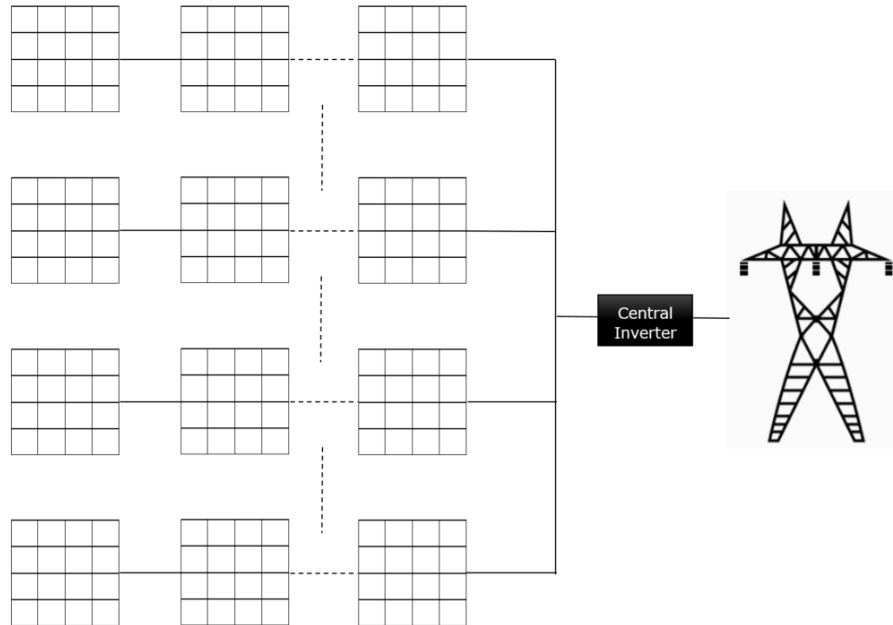


Figure 12: Central inverter is installed to series with n-amount of strings of inverters installed in parallel.

Drawbacks of central inverters are their size, noise impact and MPP mismatching. In addition a pad and combiner box are needed.[23]

2.2.5 Cascaded Inverter

Cascaded inverter can be presented as a hybrid of micro and central inverters. It has multiple H-bridges connected cascaded with the grid. Cascaded inverter is used extensively in the industry, because it is able to do medium voltage (MV) power system conversions with the use of low voltage (LV) and mature semiconductor switches.[17] Cascaded inverter is presented in Figure 13. The working principle of an H-bridge, also called as full-bridge, is explained in detail in Sections 2.2.1 and 2.6.1.

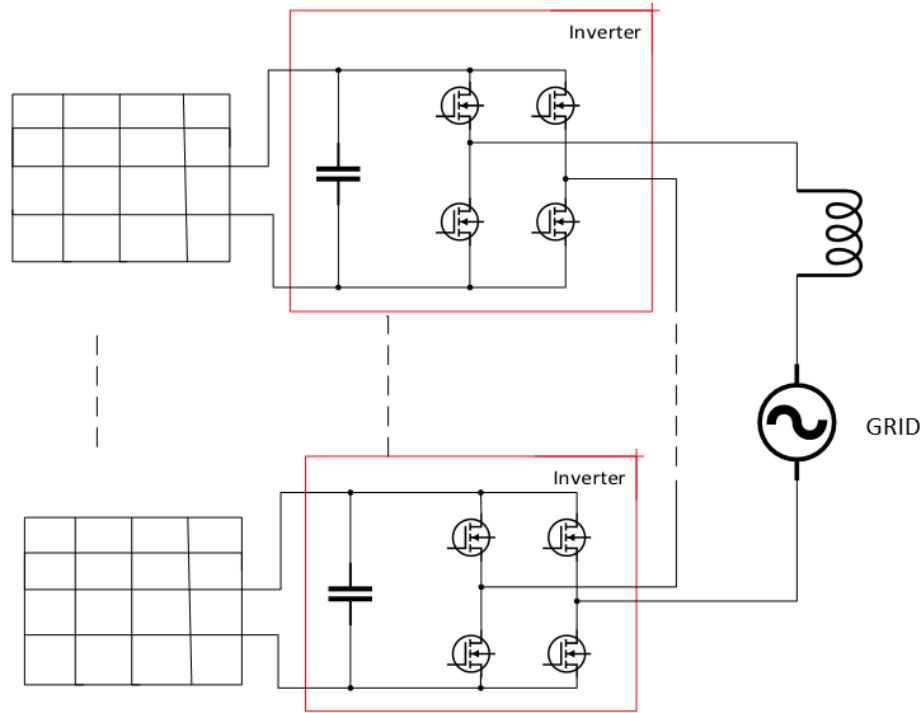


Figure 13: Cascaded inverter has multiple H-bridges connected cascaded with the grid.[17]

Like micro inverters and power optimizers (will be explained in Section 2.2.6), also cascaded inverters are able to do individual MPP tracking to each panel. In the last mentioned the AC-outputs of the inverters are connected to series, which eliminates the high boosting from LV to high voltage (HV), which is required in micro inverters.[17]

The major disadvantage of cascaded inverter is the lower DC-link voltages, which demands to use electrolytic capacitors for fulfilling the requirements considering the energy storage. To use electrolytic capacitors in cascaded inverter is obligatory, but the usage reduces the lifetime of the system. In addition the modularity of the system may be sacrificed, because inverters connected to series rely on each others and this has flow on effects to the fault tolerance of the whole system connected in series.[17]

However, the LV gain requirements increase conversion efficiency. It is verified, that compared to string and micro inverters, and to power optimizers, cascaded inverters would possibly have the highest total energy yield of the PV when real conditions, like shading, are considered.[17]

2.2.6 Power Optimizer

Power optimizer, presented in Figure 14, is a mixture of string and micro inverter. It offers better system efficiency than a string inverter and is normally cheaper than a micro inverter. Like micro inverter, also power optimizers track the MPP of individual panels, which reduces the impact of partial shading. They also provide monitoring of each panel, but do not increase the rated output power of the solar panels. The effective output voltage of the solar panels are varied by the optimizer, which allows different currents to flow through each panel in the system. Power optimizers have become a common choice for residential solar systems.[26][17]

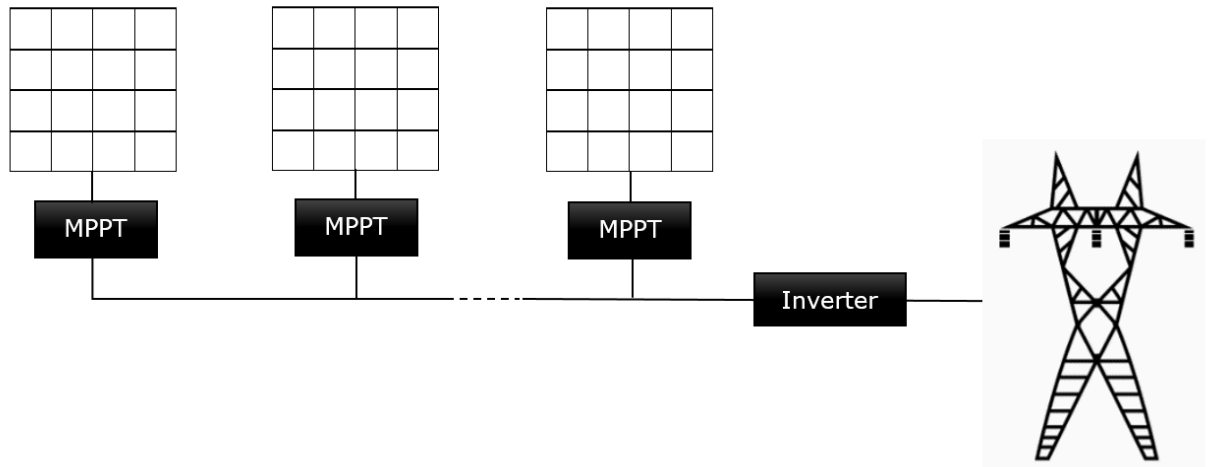


Figure 14: Power optimizer tracks MPP for every panel individually, but inverter is shared.

Power optimizers are normally integrated to the back of the panels, like micro inverters as well. Difference compared to installation of micro inverter is that power optimizers are normally within the terminal box of the solar panel. Installation to back of the panel increases the design costs, because back of the panel is hot (on sunny summer days even 80 °C) and optimizers should match to the lifetime of solar panels, which is around 20-25 years [17]. Anyway, instead of DC/AC conversion at the panel, they collect and form the DC and send it to the shared inverter.[24][17]

Several low power conversion stages reduce the system efficiency and individual MPP trackers increase the system cost. However, power optimizers increase the system efficiency compared to conventional string inverters, so conversion losses and increased costs can be compensated by increasing the energy yield by the higher total MPP in the system.[17]

Micro inverters, string inverters and power optimizers are designed to quite similar purposes, to residential and commercial installations.[24]

2.3 System Efficiency

Efficiencies of inverters have reached a high level, values are nowadays around 97-99%. For example possible integrated transformers and way of calculation affects to the value of the efficiency of an inverter and this is why micro inverters normally have lower efficiency than inverters with higher input power. Because of this, inverters with and without transformers are not straightly comparable in sense of efficiency.[5] More information about transformerless inverter topologies and topologies with transformers can be found later in this thesis.

Power, fed into inverter, affects to its efficiency. Maximum efficiency is the highest efficiency measured for a certain inverter and naturally inverter only operates temporally with its maximum efficiency.[5] Reason for this is that the maximum output power of the PV depends on the irradiation and ambient temperature and these are further dependent on the geographical location. Because of fluctuating operating conditions, solar panels are not comparable, if comparison is made on the base of peak efficiency of the solar panel or efficiency of the panel in certain operating point.[27]

Useful tool for facilitating the comparison is a weighted efficiency value. It is useful both for designers and customers since it takes into account the irradiation and temperature of different geographical locations. The most common efficiency weights are η_{EU} and η_{CEC} , also known as European and Californian efficiencies, which are obtained with the data of Europe and the Northwest of USA. This means, that the weighted efficiency is an averaged operating efficiency over an annual power distribution in the corresponded region. Therefore European efficiency is suitable to use for example in Central Europe and Californian efficiency on the other hand in Southern Europe, where the irradiation of sun is higher. η_{EU} and η_{CEC} are presented in Equations (1) and (2), respectively. η_{EU} stays for European efficiency and η_{CEC} for Californian efficiency.[27][5]

$$\eta_{EU} = 0.03 \cdot \eta_{5\%} + 0.06 \cdot \eta_{10\%} + 0.13 \cdot \eta_{20\%} + 0.1 \cdot \eta_{30\%} + 0.48 \cdot \eta_{50\%} + 0.2 \cdot \eta_{100\%} \quad (1)$$

$$\eta_{CEC} = 0.04 \cdot \eta_{10\%} + 0.05 \cdot \eta_{20\%} + 0.12 \cdot \eta_{30\%} + 0.21 \cdot \eta_{50\%} + 0.53 \cdot \eta_{75\%} + 0.05 \cdot \eta_{100\%} \quad (2)$$

where $\eta_{X\%}$ is the measured efficiency at x% of the rated power of the inverter under test.[27]

Figure 15 presents how irradiation varies depending on the geographical location on daily and yearly levels. It shows the potential of solar power around the world and also clarifies why weighted efficiency values are needed.[28] As can be seen from the Figure, Central and Southern parts of the Globe have significantly better potential for solar power than Northern parts and this is why different weighted values helps with comparison.

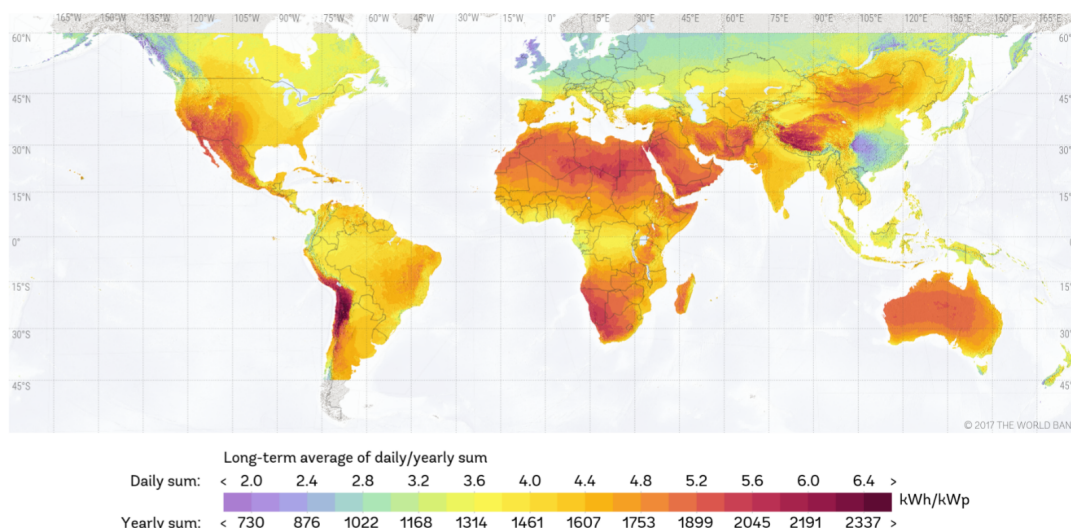


Figure 15: Photovoltaic power potential and fluctuating irradiation of sun represented globally.[28]

2.4 Current Solar Inverter Trends and Future

Industry around renewable energy sources, hence also around solar energy systems, develops all the time. At the moment the most growing sections in the field of solar inverters are 3-phase low power and 3-phase high power inverters. Currently the trend is to integrate the inverter to panel system, which is already widely used in case of micro inverters. Integrating simplifies the installation and reduces the labor costs of installers.[5]

In the future, bigger role in grid management for solar inverters has been schemed. It has been forecasted, that solar inverters will take part to power correction (PF) management and feed aligned harmonic components to the grid.[5]

Also development of the smart grid will open new possibilities for solar inverters: inverters in residential systems can in the future possibly decide, where the produced energy will be used. Electricity can be used, sold or stored, depending on the transient market situation. When working in the smart grid, fast communication between the grid and the solar system is required for the inverter.[5]

When talking about trends in the field of solar inverters, trends in semiconductor components should not be forgotten, due to their incredible important role in these devices. It is reckoned, that solar market will be dominated by inverters based on semiconductor components produced of silicon carbide (SiC). Also in the near future, inverters combined with gallium nitride (GaN) and SiC based devices are suspected.[6]

SiC and GaN are semiconductor components with wide bandgap. They offer higher efficiency, smaller size and lighter weight than conventional semiconductor devices, like MOSFETs. Nevertheless the technology behind them is comparatively novel, so price is not competitive yet with conventional technologies.[29]

Usage of switches based on these two technologies will open a whole new market,

where the efficiency of grid-tied inverters will be significantly improved. Additionally to improved inversion efficiency, the usage of SiC and GaN will open the market for thin film PV arrays. This, and devices with wide bandgaps, will open a totally new field for research.[6]

2.5 Inverter Topologies

In this Section commonly used inverter topologies are introduced and compared. Used inverter topology has a significant affect on the inverter's and further on the solar energy system's efficiency and therefore lots of research has done on the field of topologies and circuit arrangements. Since there exist many different inverter topologies in the market, only the most common ones are introduced in this Section. Topologies for micro inverters are introduced more detailed after the general introduction.[11]

Inverters can be categorized in pursuance of main topologies. These three different possibilities are [11]:

- Two-stage single module inverter
- Two-stage multimodule inverter
- Single-stage multilevel inverter

Figure 16 clarifies the difference between two-stage and single-stage topologies. Multimodule two-stage inverter is like two-stage inverter, but it just has more PV modules in the input.

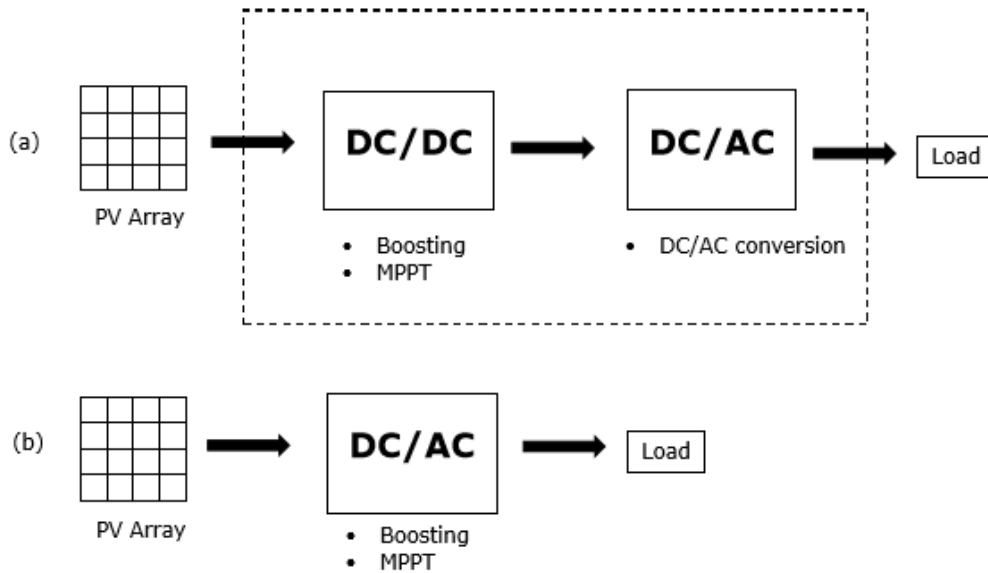


Figure 16: Two-stage power conversion (a) and single-stage power conversion (b) [11].

Conventional way to implement an inverter is with a transformer. However, this execution is bulky, heavy, difficult to install, unreliable and has poor efficiency. Nevertheless, transformer provides galvanic isolation, which is its major advantage. Galvanic isolation signifies an implementation where input circuit, which is in the case of solar inverter DC-side, is physically and electrically isolated from the output side. When galvanic isolation is provided by a transformer, input wiring does not touch the output wiring.[30][31]

Currently transformerless single-phase inverters, especially in power range of 1-10 kW, interest the solar market. They are light, cheap, small, simple and more efficient compared to conventional inverters with transformers.[6] Galvanic isolation can be provided with additional switches either on DC or AC side. However, some countries, like Germany, does not require galvanic isolation in LV-grid from inverters anymore.[6][32]

Parameters that should be considered, when designing an inverter topology or when making a decision, which one to use, are listed below.[30]

- Leakage current
- Number of MPPTs
- Output voltage
- Power semiconductors
- Input capacitance and number of capacitors
- Sum of switches
- Analysis of losses
- Reliability
- Power density
- Overall performance
- Lesser in the number of power stages

Leakage current is the major problem of transformerless topologies. It is zero, as long as DC voltage is kept constant. This can be seen from Equation (3).[30]

$$I_{leakage} = C_{pv} \frac{dV_{DC}}{dt} \quad (3)$$

As noticed in Equation (3), the question in transformerless topologies is, how to keep the V_{DC} constant. It can be done, for example, with freewheeling loops and power transmission loops. The challenge is in creating these loops, while when increasing the number of switches, also the complexity and price of the inverter increases.[30]

Freewheeling or transmission loop is needed since in transformerless inverter there is no transformer for isolation. Without isolation solar panels and grid are having electrical connections through parasitic and filter capacitors, and filter inductors and consequently the leakage current is likely to increase rapidly. This causes ripple, losses to the system and safety issues.[30]

2.5.1 Topology comparison

This Section compares and represents different topologies according to literature. Topologies are compared from the cost, performance, leakage current, MPPT, amount of switches, stress over switches and amount of needed diodes -point of view. Objective comparison without running measurements is a challenge and comparison in this thesis is done based on the references, that can be found from each paragraph. Comparison of different topologies is represented in Figure 17 and this Section is comparing topologies in a sense that they are used in transformerless inverters. Additionally has to be noticed, that even some of the topologies were normally used in three phase systems, Figure 17 only compares the amount of devices for one phase. This makes the comparison fair.

	Half bridge	H4	H5	H6	HERIC	QUAZI-HERIC	Flying capacitor	NPC
Cost	Low	Medium	High	High	High	High	Medium	High
Performance	Medium	Medium	High	Medium	Medium	Medium	Medium	High
Leakage Current	Very Low	High	Very Low	Very Low	Very Low	Very Low	Very Low	Very Low
MPPT	1	1	1	1	1	1	1	1
Switches	2	4	5	6	6	6	4	4
Stress over switches	High	Low	Low	Low	Low	Low	Low	Low
Diodes	0	0	0	2	2	3	0	6

Figure 17: Comparison of currently interesting topologies according to literature. Colours are used to point out pros and cons of each topology. Green stands for advantage, yellow for neutrality and red for disadvantage. Scale of evaluation is very low, low, medium and high.[6][30][33][34]

H5, H6, HERIC and QUAZI-HERIC are all topologies derived from conventional H-bridge, also called H4-topology. Clarifying schematics of these topologies are represented in Figures 18 and 19. Schematics are drawn with MOSFETs, but also for example IGBTs can be used. Full-bridge as for consists of two half-bridges. As also Figure 17 shows, half-bridge topology is low in cost. This is due the low amount of components in the circuit. Major disadvantages are, that voltage stress over switches is significantly high and utilization of DC voltage is low. Also harmonics in the output are high. In full-bridge topology the stress over switches is reduced, since two more switches are added. Full-bridge topology is a cost effective solution, but high leakage current and conduction losses are its major problem.[30]

H5 is an improved version of H4-topology, since one additional switch is added to it. This switch it added between DC-link and full-bridge configuration. The fifth switch makes it possible to disconnect the panels from the grid. This suppresses the leakage current efficiently. Nevertheless this additional switch have greater losses than

the other switches in the inverter, which challenges the heat dissipation procedure. Amount of devices is anyway comparatively low, which affects positively to the price and to the switching losses.[30]

H6 is an advanced version of H5. One additional switch is added either in parallel with the fifth switch, or then on the opposite side of the circuit between DC-link and full-bridge. This reduces the losses of the fifth switch and also balances the losses. Also the heat dissipation procedure is easier. Anyway the disadvantage of this topology is, that four switches are in a on-state during power transmission mode. This has a major negative affect to conduction losses, which decreases efficiency.[30]

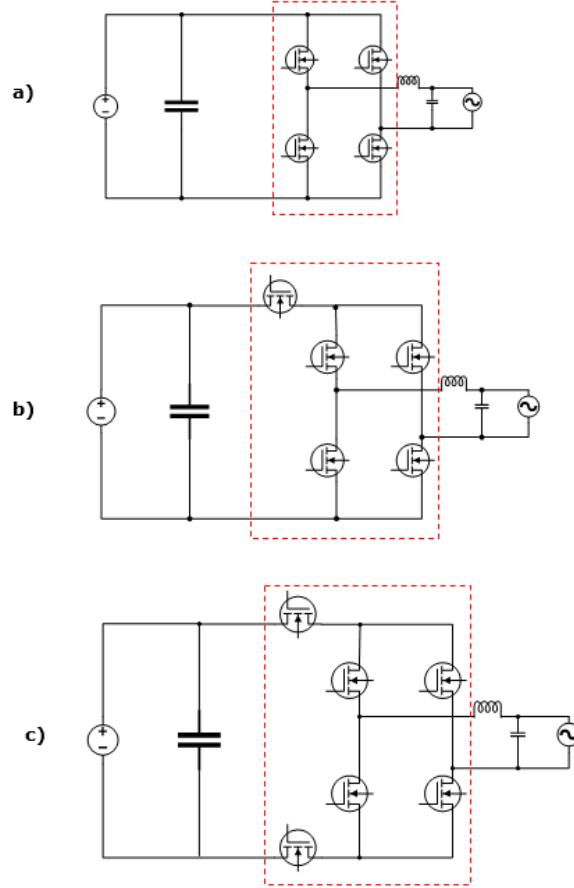


Figure 18: Schematics of a) Full-bridge, b) H5 and c) H6 topologies. Switches are surrounded by a red dash line. [6][30]

HERIC and QUAZI-HERIC -topologies have additional switches, which provide a freewheeling loop on the zero switching state. These switches are located between AC output and the bridge-configuration. This loop suppresses significantly the leakage current, which is important for transformerless topologies, as already discovered in this Section before. In HERIC and QUAZI-HERIC the current flows through body diodes of the switches during in the freewheeling loop. If fast body diodes, which recover faster, are used, the losses are reduced. Advantages of these topologies are the low leaking current and the low stress over switches. Nevertheless this

configuration demands two diodes and six switches, which increases the cost and switching losses.[6][30]

The difference between HERIC and QUAZI-HERIC topologies is the DC-side. QUAZI Z-source inverter is an improved version of an impedance source inverter (ZSI) and it overcomes the disadvantages of ZSI. ZSI is an inverter type, where split-inductors and capacitors compose a two-port network. These capacitors and inductors are connected in a shape of X and they provide an Z-source coupling for the inverter to AC load and DC source. ZSI has, compared to conventional inverter topologies, both buck- and boost ability. This is due its unique circuit topology, where no DC/DC converter is used. In addition both inductors and capacitors are used for storing energy and reducing the ripple. QUAZI-source has two operation modes: non-shoot through and shoot through. Since in PV systems the power range varies a lot and it is dependent on weather conditions, QUAZI-source is a good choice, since it can handle large power variations.[35]

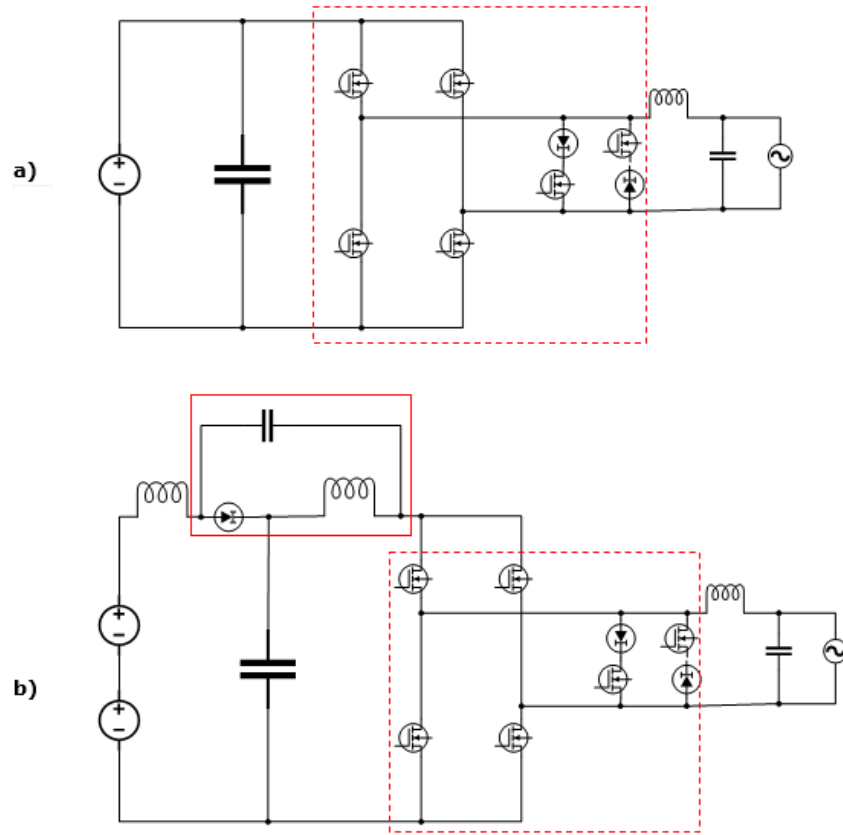


Figure 19: Schematics of a)HERIC and b) QUAZI-HERIC topologies. Switches are surrounded by a red dash line and the QUAZI-circuit is surrounded by a red solid line.[6][30]

The working principle of Neutral Point Clamped (NPC) and flying capacitor -topologies differs from conventional full-bridge -based topologies. Schematics of

both of these topologies are represented in Figure 20. NPC-topology is mostly used in three phase inverters, which are working on high power levels, in magnitude of megawatts. In NPC a clamping diode is used to connect the midpoint of the transistor to the neutral point, which generates an additional voltage level. Two transistors in series with diodes in parallel, one clamping diode, and a capacitor, are connected on the upper side of the neutral point and the same set of devices are on the lower point. The upper side generates the positive half cycle of the sinusoidal wave used in the AC load and the lower side generates the negative half cycle. Drawbacks of this topology are the unbalance of capacitor voltages and unequal loss distribution between switches. IGBTs are used in NPC-topology as switches. The main difference between conventional H-bridge based topologies and NPC- based topologies is, that with NPC, not only plus and minus potentials are reached, but voltage can also have the status of zero. Nevertheless NPC-based, but more improved topologies, are under development and already also in the market to overcome these problems. Anyway due to extent and focus of this thesis, these topologies for significantly high power levels are not examined deeper.[34]

Flying capacitor has similarities with NPC-topology, mentioned before. Nevertheless, where NPC is a diode clamped -circuit, flying capacitor is capacitor clamped. It is used in multilevel-inverters, which can also be seen in Figure 20 (b). There input has two DC sources, which represent two solar panels. Name of this topology originates from capacitors, which are floating in respect to earth's potential. Circuit of flying capacitor consists of switches, which normally are transistors, diodes and switching devices. Every part of the inverter looks similar: cells are connected to each others to nested series. Each cell consists of two transistors, anti-parallel diodes and of one capacitor. Capacitors, which are located closer to the AC-output have lower voltage and capacitors, which are located closer to the power supply, have higher voltage. Flying capacitor provides good power quality and like Figure 17 shows, the amount of needed components is relatively low, which affects positively to the price. Main challenge of this topology is, that only capacitors, that can be pre charged, can be used.[33]

As Figure 17 shows, value of MPPT is same for each topology compared. This is logical, since like mentioned earlier in this thesis, MPPT is a special characteristic of inverter.

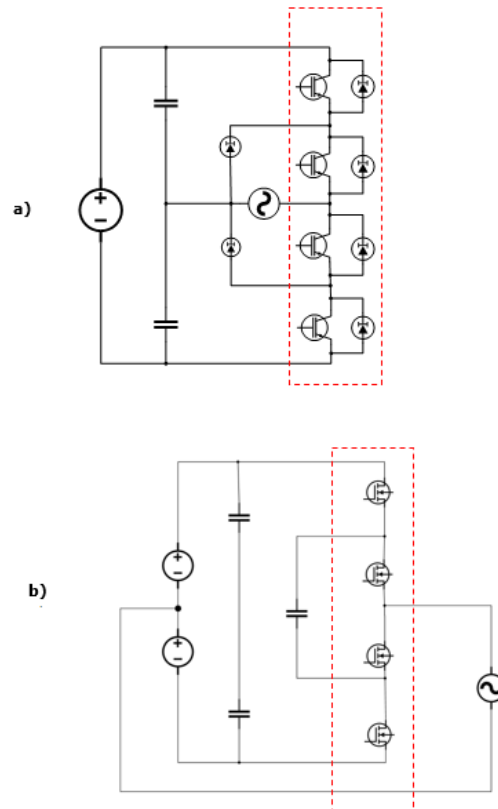


Figure 20: Schematics of a)NPC, b) Flying capacitor topologies. Switches are surrounded by red dash line and since NPC uses IGBTs as switches, also the anti-parallel diodes are drawn.[34][33]

2.5.2 Maximum Power Point Tracking

MPPT is a special feature in solar inverters. It optimizes the output power in varying temperature and radiation circumstances by controlling the load seen from solar panels so the panels work constantly in their maximum power point. In single-stage topologies, MPPT is ensured by modifying the switching algorithm. On the other hand in multi-stage topologies, DC/DC converter eases the execution of MPPT. MPP can be found from the knee-point of I-V curve of PV modules, as shown in Figure 21. MPP is the point where power reaches its highest value, as Equation (4) below shows.[4][17][10]

$$P_{MPP} = U_{PV,max} \cdot I_{PV,max} \quad (4)$$

where $U_{PV,max}$ stands for the maximum output voltage and $I_{PV,max}$ for maximum output current of photovoltaic.

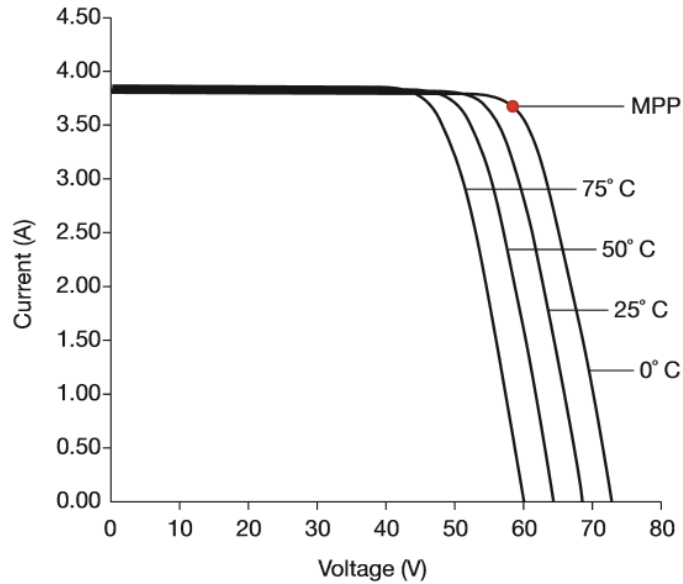


Figure 21: IV-curve shows how Maximum Power Point depends on temperature. The higher is the cell temperature, the lower is the value of voltage and further the lower is the value of MPP.[4]

As Figure 21 shows, when cell temperature decreases, voltage increases. In addition to temperature, MPP is also irradiant dependent. Output current of photovoltaic is higher, when sun shines brighter and the other way round, when the amount of light is less, also amount of current is smaller. Because circumstances are changing a lot during the year, MPPT has an important role in solar inverter.[4]

For tracking the MPP several methods exist. Mostly used logic is called Perturb and Observe (P&O). Its popularity is based on its simplicity and minimal amount of required parameters. Drawback of P&O is its assumption that the IV-Curve of PV has only one apparent MPP. Figure 22 clarifies the P&O method.[17]

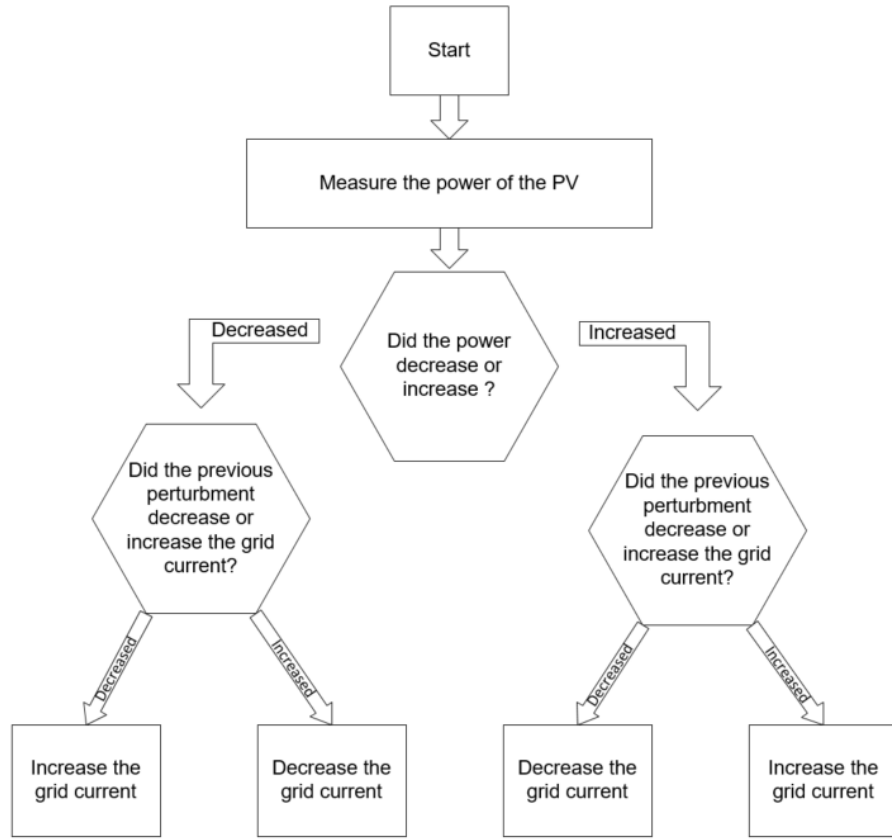


Figure 22: The most common method for MPPT in grid-tied solar inverters is Perturb and Observe.[17]

2.6 Topologies for Micro Inverters

Because this thesis focuses on micro inverters and used topologies in them differs partly from bigger scale inverters due to the voltage levels, this Section familiarizes the topologies used in micro inverters. Due to extent of this thesis, only those topologies, that were found during the tear downs, are represented. More about tear downs can be found in Section 3.

Micro inverter topologies can be divided to single-stage and multi-stage topologies but most research has been made on the field of the last mentioned. The amount of stages signifies the amount of power conversions. The efficiency of micro inverters is around 95-97% [15] and average lifetime is approximately 25 years. Reasons for high lifetime are low rise in internal temperature in the inverter and deletion of bulky electrolytic capacitors. Most of the micro inverters are designed to operate grid voltages with PF 0.95-0.99 (values taken from Section 3.5.2) and maximum THD is limited by IEEE regulations.[10]

As explained in Section 2.2.2, each micro inverter has an individual tracking for MPP. With proper MPPT, output power can be increased approximately by 11 %.

In single-stage topologies, inverters are designed to ensure the MPPT by modifying the switching algorithm of the inverter, whereas in multi-stage topologies, DC/DC converter is easing the execution of MPPT. MPPT uses the voltage and current level optimization for tracking the MPP. Manufacturer provides the voltage and current characteristics of a PV, which helps with defining the operation mechanism of MPPT. If frequency or amplitude of the step size are chosen wrongly, the reliability of the system may decrease considerably.[10]

Like mentioned above, micro inverters must be easy to install and fit to the roof of a domestic building. To be more attractive in the market, micro inverters should be feasible for grid connection as well as home based applications. Inverter must be able to shape the current to be as close pure sinusoidal wave as possible and to offer high conversion efficiency with optimization of output power.[10]

Typical components of a micro inverter are listed below [10]:

- DC/DC converter
- Inverter
- Control circuitry
- Protection scheme
- Utility interfacing transformer

And these components are additionally recommended [10]:

- Surface mounted inductors
- Fast recovery diodes
- Low Equivalent Series Resistance (ESR) capacitors

An integrated micro inverter is located in the back of the panel [21] and the back of the panel can get really hot. On a sunny summer day, micro inverter must be able to stand even 80 °C, so thermal modelling can increase the life time of micro inverter. This can be explained by Arrhenius equation, which represents the failure rate of a component, in sense of appearances of faults caused by temperature. Because of demanding thermal requirements of micro inverters, proper thermal modelling is often required. In addition to exacting thermal conditions, reliability and lifetime of a micro inverter depend on the lifetime of different components in the solar system.[10]

2.6.1 Full-Bridge

H4-inverter, also called as full-bridge inverter, consists of two half-bridges. Working principle of this conventional inverter topology is already explained in Section 2.2.1 and Figures 7 and 8 represent it.[36] Upper switches are switched with high frequency, in magnitude of some kHz, and lower switches are switched on grid frequency, which is 50 Hz in Europe.[37]

In H4-topology four semiconductor components are used as switches. Upper switches, S1 and S4, are connected to each others drain-to-drain and lower switches, S2 and S3, are connected to each others source-to-source. Additionally S1 and S2 are connected source-to-drain, as well as S4 and S3.[36]

Full-bridge is preferred over half-bridge on higher voltage levels, since with the same DC input voltage the AC output is twice as big as compared to output of half-bridge. This is because the current through switches and the output current are half of the same currents for half-bridge. This is a major advantage at high power levels, since less paralleling of devices is required.[36][6]

2.6.2 H5

H5 is an improved version of conventional H4-inverter, explained in previous Section 2.6.1. In addition to full-bridge, it has one additional switch, which makes it possible to disconnect the solar panels from the utility or local load. This suppresses the leakage current but also has bigger losses than the other switches, which makes heat dissipation more complex. Also an additional switch increases the cost of inverter.[30] Working principle of H5-topology and also of other topologies basing on full-bridge topologies, can be found more detailed in Section 2.5.1.

2.6.3 Cyclo Inverter

Cyclo inverter, shown in Figure 23, is a single stage inverter topology, that features higher efficiency and low components count compared to conventional two-stage inverters, such as flyback-converter with an H4-topology, where an additional HV diode is needed for rectification, whereas it is not needed in cyclo inverter. This additional diode can be seen in Figure 24. Moreover, HV side MOSFETs are not required to have fast body diodes, due to no hard commutation in the switching.[38]

The primary side of cyclo-inverter is a series resonant tank, comprising of a series capacitors and inductor. The resonant tank gets excited by the voltage pulse generated by the LV bridge, resulting in a sinusoidal resonant current. The secondary side is cyclo inverter, which also can be thought of as a bi-polar voltage doubler rectifier. Its ideal working principle is following: resonant primary current transfer to secondary side scaled by transformers turns ratio, the positive half of the sinusoidal current passes through one pair of the back-to-back MOSFETs to charge one of the secondary capacitor, the negative half of the sinusoidal current passes through the other MOSFETs branch to charge the other secondary capacitor, the sum of both capacitors' voltages is equal to the output voltage.[38]

2.6.4 Flyback Converter

As tear downs in Section 3 will show, major of the reverse engineered micro inverters use variations of flyback converter for galvanic isolation. Flyback converter is derived from buck-boost converter. Since one additional winding is added to the inductor, it works as electrical isolator.[36]

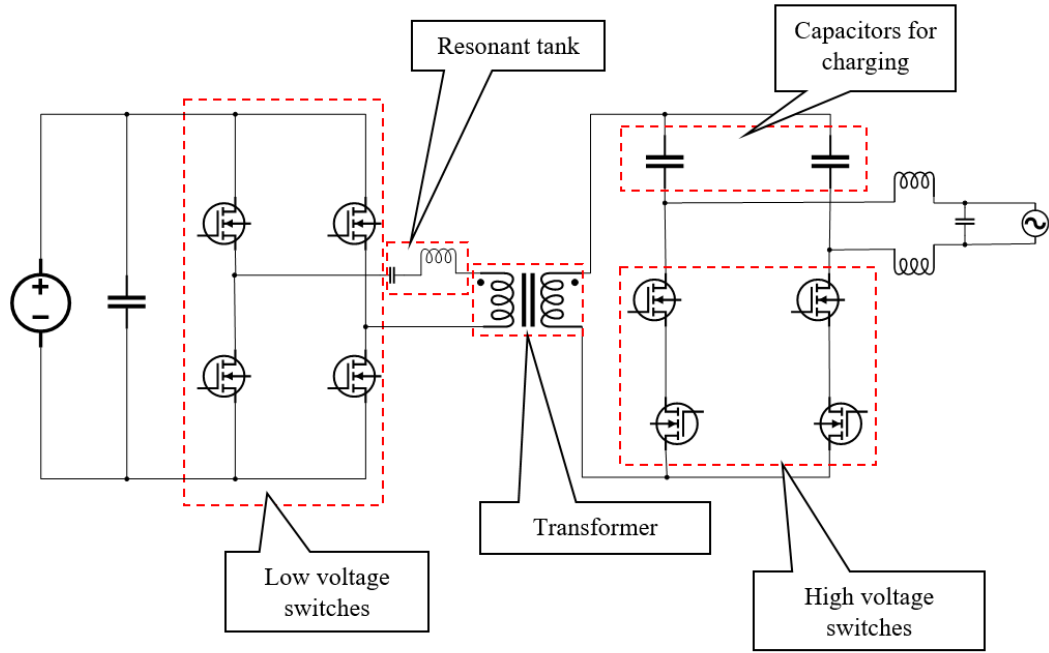


Figure 23: Schematic of a cyclo inverter. LV and HV switches, resonant tank, transformer and capacitors for charging are surrounded by a red dash line.

Figure 24 shows the on-state of flyback converter. In on-state the switch, which is a MOSFET, is closed, so the current is flowing through the primary winding and the primary winding is connected to the input. The current and magnetic flux is increasing on the primary side and the energy is stored in the transformer. Voltage is induced on the secondary side of the transformer, but it is negative, which makes the diode working reverse biased. This happens due the polarity of the winding. Voltage increases first rapidly on the secondary side, and then starts to balance. This is how the winding on the secondary side supplies energy to the load.[36]

The off-state of flyback converter is represented in Figure 25. On the off-state the MOSFET is open. This makes the magnetic flux and current on the primary side to decrease. Simultaneously the voltage on the secondary side is positive and the diode is conducting. On the off-state the core of the transformer charges the secondary-side coil again and supplies it to the load.[36]

The variations, used in the reverse engineered inverters, will be explained in Section 3.

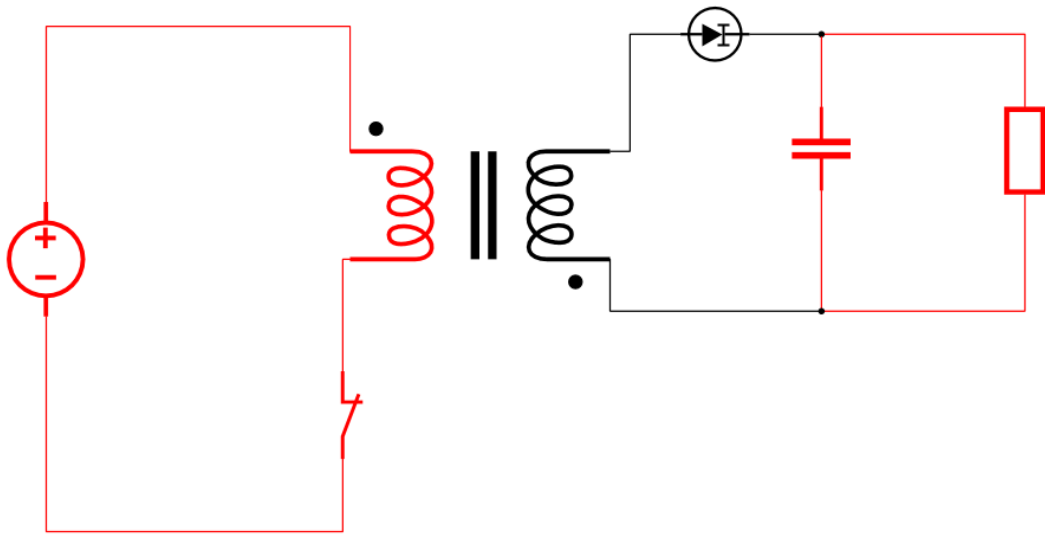


Figure 24: On-state of flyback-converter. Red line shows how the current is flowing on the on-state, when the switch is closed.[36]

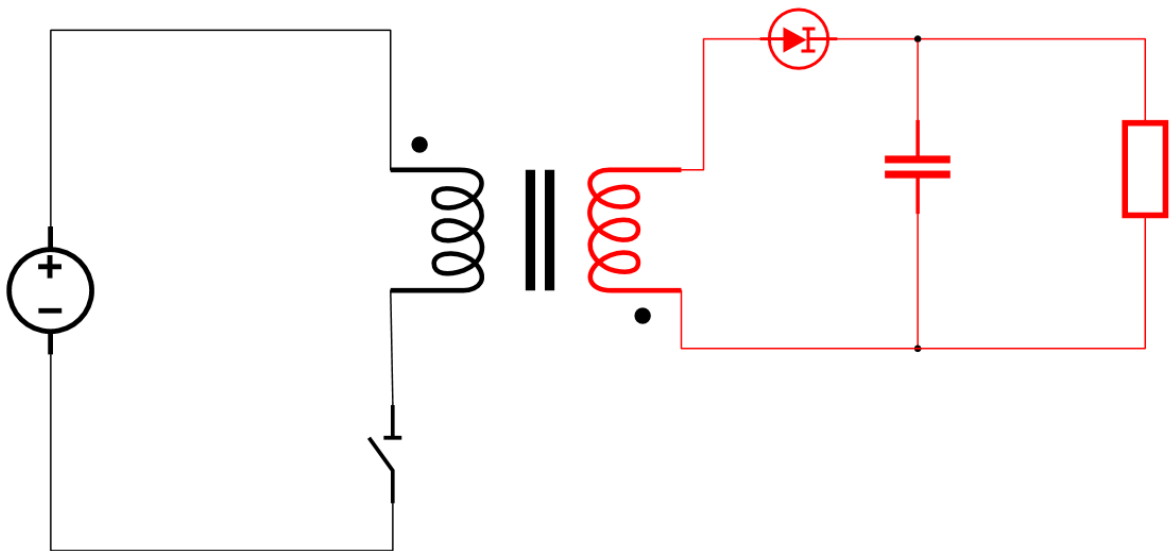


Figure 25: Off-state of flyback converter. Red line shows how the current is flowing on the off-state, when the switch is open.[36]

2.6.5 Magnetic Components

Major challenge of micro inverter is that the output voltage of one solar panel is small compared to the voltage needed in grid or in local load and the stepping up should be made with the best possible efficiency.[10] Output voltage of one solar panel is around 40-60 V and it must be stepped up to more than 200 V.

Stepping up the voltage in case of micro inverter is conventionally done by DC/DC-converter, also called as boost-converter and galvanic isolation is provided by either a transformer, or flyback converter. Nevertheless, transformers are heavy, bulky, and increases the size and the cost of an inverter.[10] In addition to providing galvanic isolation, transformers are also used for adjusting the voltage level after inversion, so the AC voltage reaches the correct level for grid interconnection. Also together with inductors, transformers smoothen the waveform of AC voltage.[4]

Transformerless topologies tend to be 1-2 % more efficient than topologies with a transformer, but then providing galvanic isolation and avoiding leakage current is more difficult [10]. In inverters, which are using transformerless topologies, the galvanic isolation can be provided by additional switches either in primary (DC) or secondary (AC) side. If these additional switches are placed in the primary side, the secondary side has fewer switches in the conduction paths, which leads to better proficiency.[6]

In addition to transformer, inductor is an another important magnetic component of an inverter. After voltage is boosted and inverted, it is raw and triangular, but when it is fed through inductor and transformer, it is smooth and sinusoidal and ready for grid interconnection.[4]

Magnetic components are material and labor intensive and their cost is relatively high. Biggest reason to their high cost is the price of iron and copper. The use of transformer might decrease the efficiency, which has also indirect affect to the cost of the system. The use of magnetic components leads also to losses.[4] Main losses can be divided to three categories:

- Core losses
- Gap losses
- Conductor losses

Core losses are losses that originate from magnetic material. These are for example iron laminations, sintered powdered materials or magnetic ribbon. As for gap losses are a result for example from the gap in between the magnetic material, like two core halves in a transformer. Conductor losses are the resistive losses in wires and coils around magnetic cores. These losses should be taken into account and minimized in a good inverter design.[4]

2.7 Country and Grid Regulations

A conventional electrical grid consists of generators, transmission and distribution lines, and utility, commercial and residential loads. When the amount of decentralized energy production increases, the energy system has to be more flexible to be able to work reliably[17]. When the quantity of distributed generation grows, also grid must be expanded and developed in a way, that building a smart grid is possible. Also the demand response have to work better, when more distributed generation will be added to the current network. Integration of areas balances the energy variation and enables the use of transient energy capacity and stored energy.[39][3]

With distributed generation, customers are part of the electrical transmission system as customers, but also as sellers. Because of the varying irradiance of solar, customers switch quickly from consuming electricity to produce it or other way around. Grid has to be ready for these changes. The inflow of residential LV grid-tied inverters has forced to creation and development of new standards.[17]

Regulated parameters are listed below [17]:

- PF
- THD
- Voltage range
- Frequency Range
- Anti-Islanding
- DC-injection

Power factor (PF) is defined in Equation (5). P stays for real power and S for apparent power.

$$PF = \frac{P}{|S|} = \cos(\phi) \quad (5)$$

PF must stay above 0.95, both lagging and leading. PF=0.95 means +/- 18.2 ° of V-I phase angle. When PF stays above limits mentioned before, inverter operates in stable and static conditions i.e the output power is steady and grid voltage and frequency are inside the limits.[17]

One regulated value is Total Harmonic Distortion (THD). For less than 69 kV systems, according to IEEE, it is 5 % [40]. THD measures the present harmonic distortion in the signal and it is defined as following:

$$THD\% = 100 \cdot \frac{\sqrt{\sum_{n=2}^{\infty} H_n^2}}{H_1} \quad (6)$$

where H_n^2 stays for the root mean square voltage for the nth harmonic and H_1 for the fundamental frequency.[17]

A grid-tied inverter must be constantly aware of the operating status of the grid. If voltage or frequency of the grid surpass a certain level, inverter must be disconnected.[17]

Islanding means a condition where distributed generation continues to feed power, even though the grid has failed and suffers for example about electrical black out. This is dangerous, because there can be workers on the power line who assume, that the circuit is not powered. In addition to danger of life, devices connected to utility grid can automatically re-connect them selves to the grid because of islanding. A technique to prevent this dangerous behaviour is called anti-islanding. Fast anti-islanding is necessary, so distribution system works efficiently and safely. Strict frequency control is needed for balancing the load and generation. Without control the islanded circuit will be violated and this leads to abnormal voltages and frequencies.[41] In case of anti-islanding, the disconnect of the inverter should happen within few seconds and reconnect should happen approximately after one minute.[17][5]

Standards provide the limits for acceptable values for voltage, frequency and DC injection[17]. These limits variate on different regions, since the transmission grid does not work under equal voltages and frequencies around the world.

2.8 Semiconductor Components

When connecting solar system to utility grid, semiconductor components have a significant role. Their purpose is to provide stable, efficient, reliable and clean energy conversion.[6] Always, when talking about MOSFETs in this thesis, power nMOSFETs are meant. Because of limited extent of a master's thesis, only those semiconductor components are introduced, that are used as switches in reverse engineered inverters. These reverse engineered inverters are introduced in Section 3.

Semiconductor is a material that has better electrical conductivity than insulator but worse than metals. In power electronics, semiconductor components like MOSFETs, IGBTs and thyristors, are used as switches. Switching and conduction losses of the transistors and diodes have a crucial role in inverter's efficiency and this is why considering semiconductor components when talking about inverters is important [42].

In this thesis power MOSFETs, thyristors and IGBTs are discussed and introduced. In micro inverters the usage of MOSFETs instead of IGBTs or thyristors makes sense and reason can be found from voltage levels. Although MOSFETs and IGBTs can be used quite similarly, IGBTs are suitable for larger voltages than MOSFETs and because voltages in case of micro inverters are comparatively small, normally only MOSFETs are used.[4]

In Figure 26 the power and switching frequency of thyristor, IGBT and MOSFET are compared. As can be seen, MOSFETs function on highest switching frequency, but on lowest power level and thyristors function on the highest power but on the lowest switching frequency. IGBT is in the middle of these devices in both power and switching frequency.[36]

As discussed in Section 2.2, in solar inverters conventionally MOSFETs or IGBTs are switched rapidly and this turns the DC on and off. As a result AC is produced.[23]

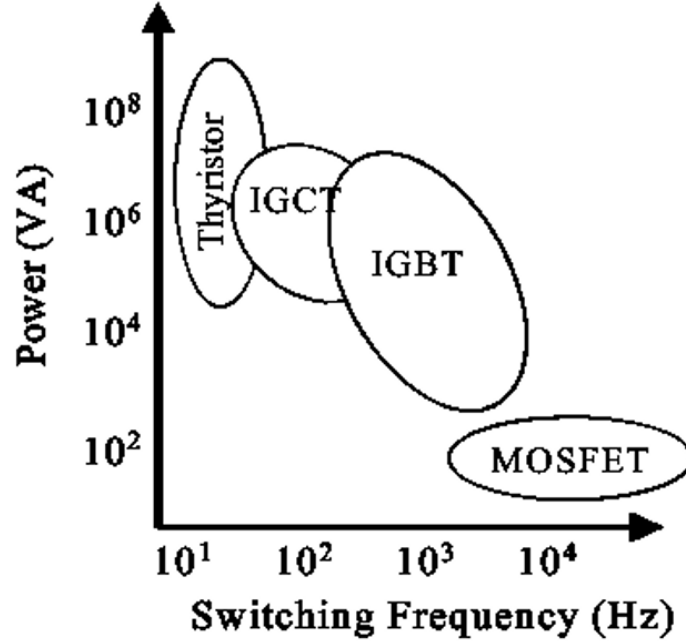


Figure 26: Comparison of power and switching frequency of thyristor, IGBT and MOSFET. Also IGCT is mentioned, even though it is not deeply represented in this thesis.[36]

Conventional way to place switches is an H-bridge configuration, which consists of four switches. Working principle is introduced in Figures 7 and 8. Because in solar inverters semiconductor components are used mainly as switches, their main requirements are [43]:

- Low conduction losses
- Low switching losses
- Ruggedness
- Avalanche capability

Conduction losses are determined by how much operating current and on-resistance are produced in the MOSFET. Avalanche capability tells how much energy the MOSFET can withstand under avalanche conditions [43]. Avalanche means that the maximum value for V_{DS} , which is the voltage between the drain and the source, is exceeded and current rushes through the MOSFET. The higher the avalanche value of the MOSFET is, the more rugged it is.[43]

In residential, approximately 5 kW systems, the cost fraction of power semiconductors compared to the total cost of inverter is approximately 8% [42].

Switch selection of inverter has many approaches. Since this thesis focuses on micro inverters, the natural approach is efficient-point of view, since the market of

micro inverters is efficiency driven. If talking about full-bridge -based topologies (H4, H5, H6, HERIC), the upper switches of the bridge are working on a high switching frequency (in the range of kHz) and the lower once are working on grid frequency, which is 50 Hz in Europe. When upper switches are switching on high switching frequency, up to 80-100 kHz, they are cycle-by-cycle exposed to hard commutation, which is the state, where the body diode is not fully recovered when the switch is switched already on again. The risk of hard commutation is small for the lower switches, since they are switching so seldom.[37]

IGBTs can withstand better hard commutation compared to the MOSFETs, since they have significantly lower reverse recovery charge of the body diode compared to MOSFETs. This would be an advantage for the upper switches in the H-bridge, since the exposure to hard commutation, like explained in the previous paragraph. Anyway, a contradiction here is, that MOSFETs offer better efficiency at high switching frequencies. This means, that especially for micro inverters, MOSFETs with fast body diodes, which are must in this case, are better choice for the upper switches. With good digital control the risk of hard commutation can be minimized.[37]

As the lower switches in full-bridge -based topologies are switching with low frequencies, in their case conduction losses are more important factor than switching losses. Also here MOSFETs are more beneficial, since the current flowing through these switches is comparatively low. Since the risk of hard commutation is low on the lower switches, MOSFETs without fast body diodes are enough. Naturally MOSFETs with fast body diodes would provide additional benefit, since the risk of hard commutation exists. Also from the economy of scale point of view this so called over engineering would be in some cases beneficial.[37]

2.8.1 MOSFET

As explained above and in Section 2.2, MOSFETs are used in inverters as switches. nMOSFET is controlled by voltage. A symbol of an n-channel MOSFET is introduced in Figure 27 below.[44]

When MOSFET is fully on, it equals approximately to a closed switch with extremely quick switching time (from few tens of nano seconds (ns) to few hundreds of ns). Switching time depends on the device type. nMOSFET achieves on-state, when the voltage between gate and source, V_{GS} , is above the threshold voltage $V_{GS(TH)}$. [36] $V_{GS(TH)}$ is the minimum voltage required to form a conduction channel between source and drain.[43]

One important parameter, when considering MOSFETs, is R_{DS} , which is the resistance between the drain and the source. During on-state, R_{DS} is extremely low and marked as $R_{DS(ON)}$. Whereas during off-state, when MOSFET equals to open switch, R_{DS} is extremely high and is marked as $R_{DS(OFF)}$. $R_{DS(ON)}$ increases rapidly with the increasing blocking voltage [36]. Blocking voltage is the maximum voltage MOSFET can stand [43].

$R_{DS(ON)}$ determines the power losses and heating of the power MOSFET. The lower the R_{DS} is, also the lower are the power losses in the device and the cooler it will operate. The importance of this feature increases when the operating temperature

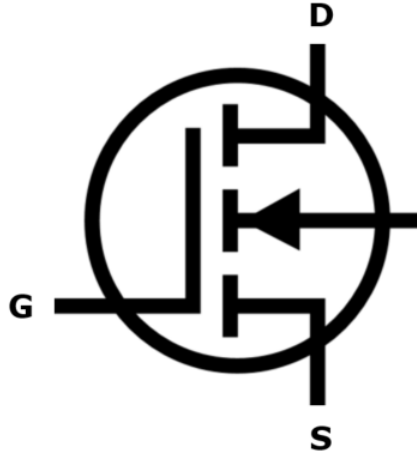


Figure 27: Symbol of an nMOSFET. D stands for drain, S for source and G for gate.[36]

increases and in the applications, whose operating temperature exceeds 125 °C, this is particularly important.[43][36] Like mentioned before in this thesis, the operating temperature of micro inverters can reach quite high levels even outside of the housing, so switches inside should be able to stand high temperatures for long times.

Low $R_{DS(ON)}$ decreases the assembly costs and reduces the amount of needed parts. Also low $R_{DS(ON)}$ often eliminates the need of parallel MOSFETs, which improves the reliability and lowers the total costs of the system.[43]

Conventional HV MOSFETs are planar and twenty years ago so called superjunction MOSFETs were introduced. They have an heavily doped current path compared to conventional HV MOSFETs, which further offers decrease of $R_{DS(ON)}$ with smaller chip size. Normally, when decreasing the $R_{DS(ON)}$, chip size is enlarged. Nevertheless in case of superjunction MOSFET, with certain compensation structure the chip size can be decreased. Further, the smaller chip size decreases the parasitic components in MOSFET, which leads to smaller switching losses.[45]

2.8.2 Thyristor

Also thyristors can be used as switches. The working principle differs from MOSFETs and IGBTs, since thyristors cannot be switched off. Thyristor switches itself off, when current crosses zero. As Figure 26 shows, thyristors are suitable for high power levels and for low switching frequencies. Thyristors are controlled by current, whereas MOSFETs and IGBTs are controlled by voltage. [36]

Figure 28 represents the symbol of thyristor[36]. Thyristors and IGBTs are normally paralleled, because they are designed for higher voltages than MOSFETs. Nevertheless IGBTs have faster switching time compared to thyristors. Thyristors are normally used in a full-bridge configuration in current source inverters.[44]

In a thyristor, current flows from anode to cathode. When it is on off-state, it

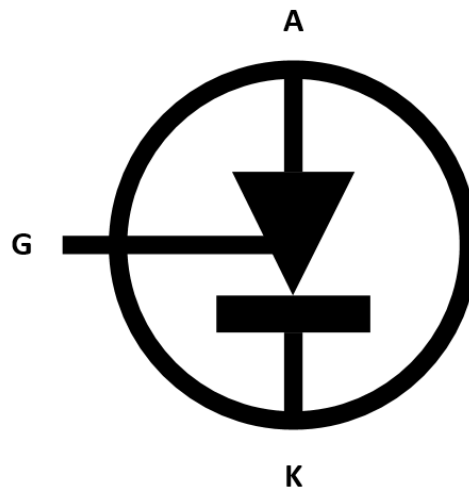


Figure 28: Symbol of a thyristor. A stands for anode, K for cathode and G for gate.[36]

blocks forward polarity voltage and does not conduct. Thyristor has lots of similarities with a diode. Anyway unlike diode, thyristor only starts to conduct, when a voltage pulse is fed to the gate. This voltage pulse has to be big enough with relation to cathode.[36]

Once thyristor is conducting, the gate current can be removed. When thyristor is latched on, gate cannot turn it off and it conducts as a diode. Conduction continues until the anode currents tries to go negative. Then the thyristor is turned off and current goes to zero. After this, the gate has a possibility to regain the control over the device and it can be turned on again. The state, when thyristor can be turned on again, is called as forward-blocking state. Other possible states are reverse-blocking state and on-state.[36]

2.8.3 IGBT

IGBTs can also be used as switches. They create a PWM-output that is smoothened to sinusoidal AC. This is explained in Section 2.2. As Figure 26 shows, IGBT is normally used in devices with higher usage power than MOSFETs. Figure also shows, that the power range of IGBT is the widest compared to thyristors and MOSFETs. Figure 29 represents the symbol of IGBT.[36]

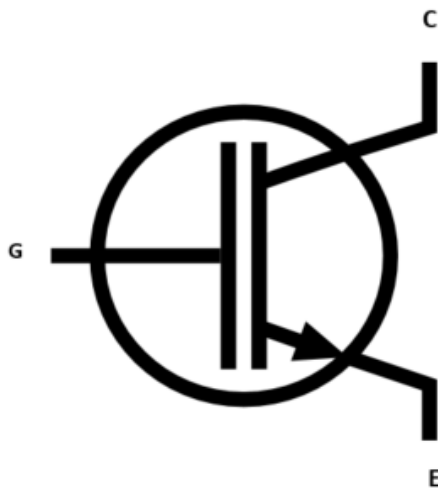


Figure 29: Symbol of a IGBT. C stands for collector, G for gate and E for emitter.[36]

Like in MOSFET, also in IGBT the gate is insulated, as its name, Insulated-Gate Bipolar Transistor, also tells. This means, that in practise, IGBT combines a MOSFET and bipolar transistor. When looking from collector, IGBT remains a bipolar transistor, but it is controlled by a MOSFET. IGBTs are controlled by voltage, as MOSFETs. When switching from on-state to off-state, IGBTs are slow compared to MOSFETs.[46]

As MOSFETs, also IGBTs require small amount of energy for switching the device. This is due to the high impedance gate. The on-state voltage in IGBTs is small, also in devices with high blocking voltage ratings. In addition IGBTs are able to block also negative voltages. Turn-on and turn-off times of IGBTs are approximately $1 \mu\text{s}$ and available voltage ratings are in magnitude of 1700 V and 1200 A.[36]

3 Tear Down and Reverse Engineering

For the practical part of this thesis, four micro inverters were ordered, teared down and reverse engineered. The goal was to evaluate the used semiconductor components and identify the used inverter topologies. These inverters are also compared with each others. Micro inverters, that were teared down, are marked in this thesis as inverter A, inverter B, inverter C, and inverter D due to privacy protection.

Also a schematic of each inverter can be found from this section. Schematics are made by the author using multimeter to identify connections between components. This section contains some assumptions of the author. Symbols, that can be found from the Schematics, are explained in Figure 30.

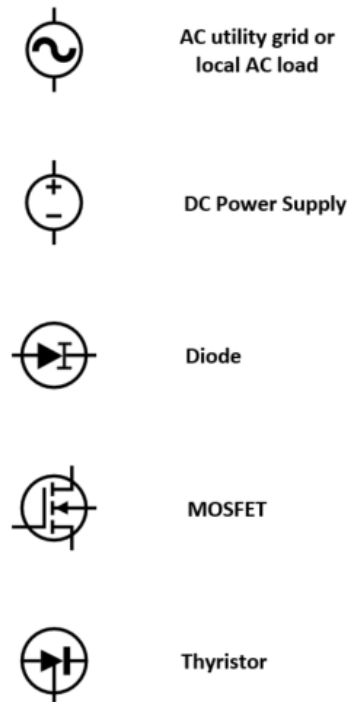


Figure 30: Symbols used in schematics.[36]

3.1 Micro Inverter A

Figure 31 shows the first opened inverter, inverter A. Inside of the housing the PCB was covered with black soft foam, which material is unknown. This foam is presumably used for heat dissipation, because electrical components generate power losses which appear as heat. In addition it presumably protects components mechanically. Housing of the inverter works as a heat sink and this foam establishes a path for the heat to reach the housing. It is needed, since the thermal conductivity of this foam is much higher than air's.



Figure 31: Open housing of inverter A.

Figure 32 shows the PCB of the Inverter A after the soft foam is manually removed.

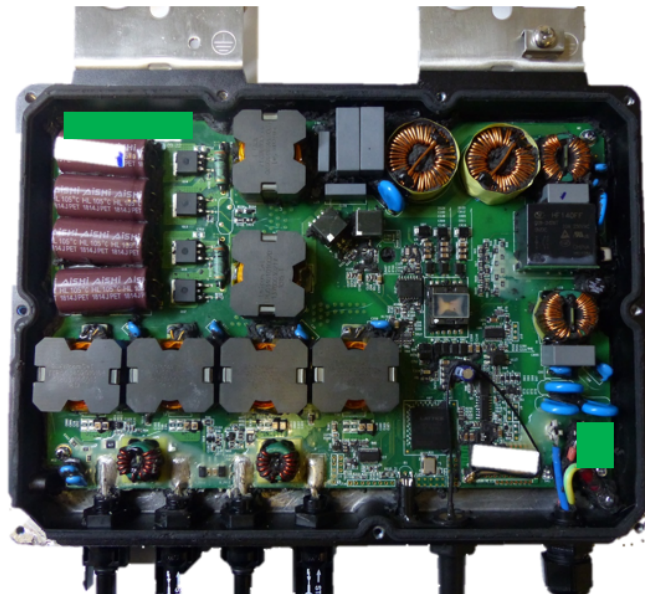


Figure 32: Open housing of inverter A when the insulator material is removed.

As can be seen from Figure 33, Inverter A has two input channels. Merging two channels into one inverter reduces installation work, because instead of installing two inverters on the roof, only one has to be installed. Additionally less money and material is spent to housing, since it is combined. Merging two channels to one inverter also reduces the amount of needed components, as can be seen from Figure

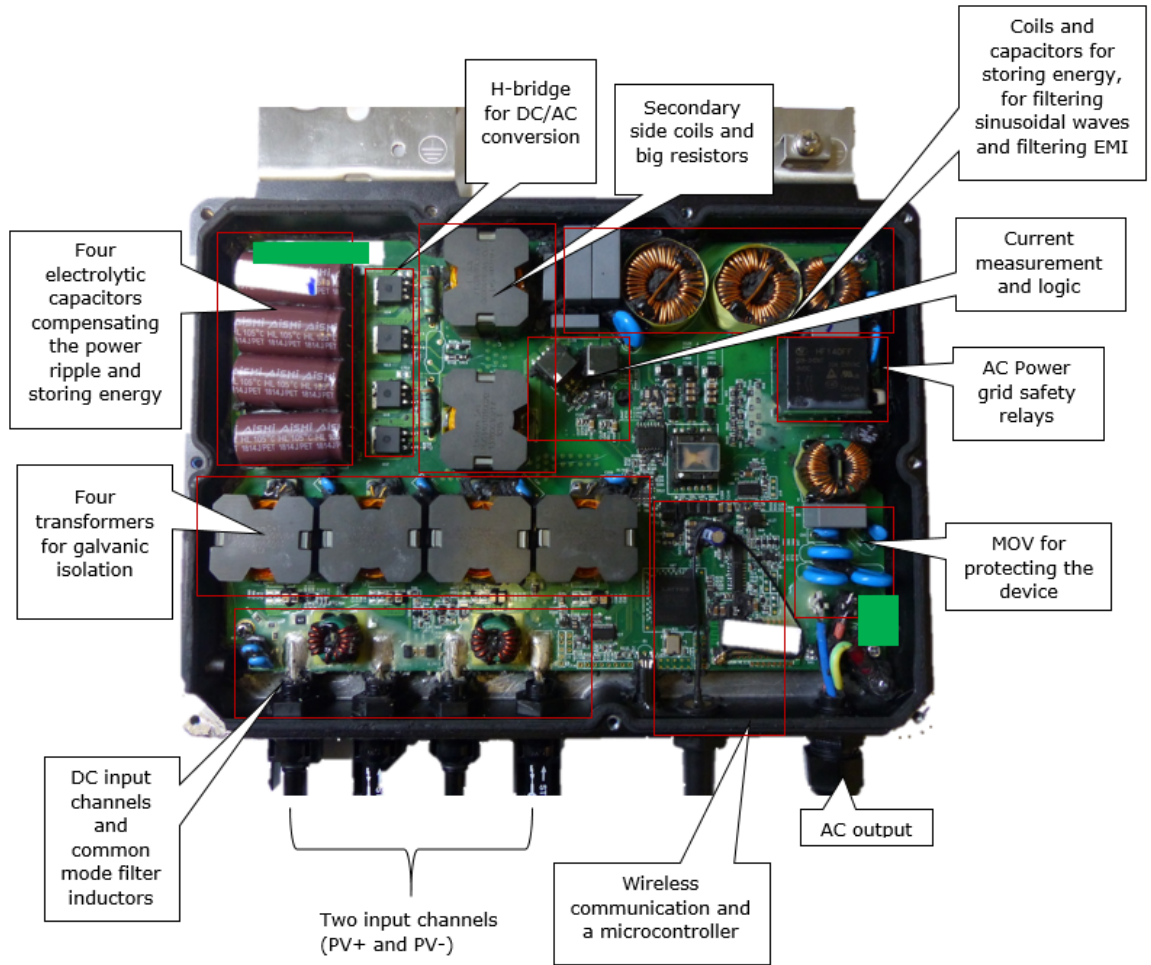


Figure 33: Inverter A with clarifications of different parts.

33: after individual transformers and MPPTs, only four electrolytic capacitors and one H-bridge are needed. Nevertheless, the voltage range is larger, which naturally leads to bigger and more powerful components.

Both channels of inverter A has two flyback converters connected in parallel and each flyback converter uses two LV MOSFETs, connected in parallel, for switching. LV switches can be seen in Figure 34. Before transformers, the common mode inductors limit the input current for example in case of a short circuit.

Inverter A has four electrolytic capacitors after flyback converters and MPPT-state for smoothing the power ripple and for storing energy. Using electrolytic capacitors is a conventional way, however according to literature, the use of electrolytic capacitors reduces the lifetime of the inverter. This is because the lifetime of electrolytic capacitor decreases when ambient temperature increases.[10][8]

After electrolytic capacitors, DC/AC inversion is done by conventional H4-topology, where MOSFETs are used as switches. The working principle of H4 is explained in Section 2.6.1. After inversion the PWM voltage is smoothened to pure sinusoidal waveform and EMI is filtered. After inversion the current is measured, so

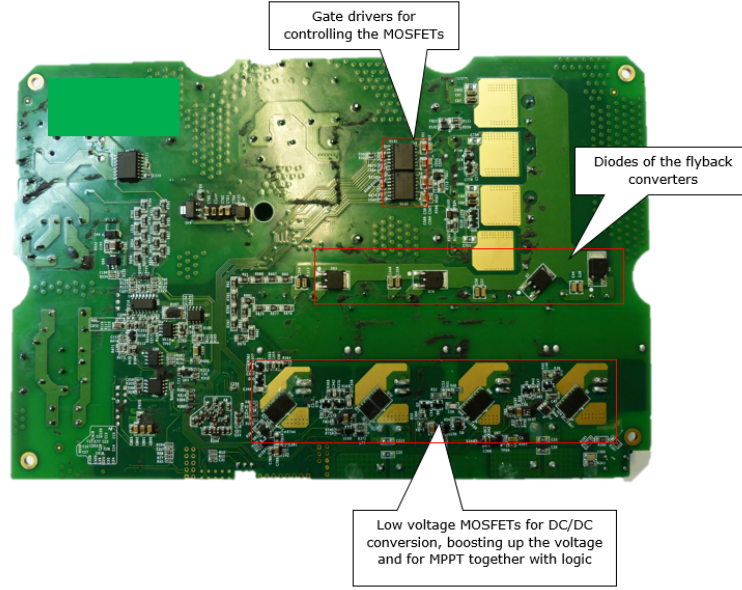


Figure 34: Back side of inverter A when the insulator material is removed.

it matches with grid in phase and amplitude. AC-current measurement part also helps with inserting the power in such a way, that reactive power is compensated.

Inverter A has a safety relay, that disconnects the inverter from the grid, if grid has a failure. Relay works with the limitations as explained in Section 2.7. Right before AC output, Metal-Oxide Varistor (MOV) or with other words varistors, protect the device from over voltages, caused for example by lightning strikes.

Microcontroller, as its name says, controls the device. It is an integrated circuit that consists of central processing unit (CPU), memory devices, timers, counters etc.[47] Wireless communication provides information about the inverter and solar panel. It for example records continuously solar plant data, gives an alarm if a failure occurs and tries to detect operational failures as early as possible.[48]

Datasheet of inverter A provides the information of output power as Volt-Ampere (VA). VA is a unit of complex power (S), presented in Equation (7).

$$S = P + jQ \quad (7)$$

, where S stands for complex power, P for active power, Q for reactive power and j for imaginary unit.

Providing the output power as VA stands for that inverter A feeds both active and reactive power to utility. In addition the current measurement part of the inverter advocates for reactive power compensation. So, a conclusion can be done, that inverter A is able to compensate reactive power.

Figure 35 represents the schematic of inverter A. It shows the paralleled flyback converters and LV MOSFETs connected in parallel, as mentioned earlier in this Section. The function of conventional flyback converter is explained in Section 2.6.4 and as schematic shows, inverter A uses a variation of it. As can be seen, both channels use paralleled flyback-conversion.

Using paralleled flyback converters instead of using one more powerful flyback unit may be beneficial on higher power levels. Some advantages of paralleling flyback converters are that due to redundancy, they provide higher system reliability, increase the effective switching frequency, which as for decreases the current pulsations at the input/output. It also allows standardization of low-power modules where a number of these can be paralleled to provide a higher power capability. Also, with this topology, higher output voltage from low input voltage is easier to achieve, and as several transformers can have lower amount of turns ratio, is amount of leakage inductance reduced.[36][49]

Paralleled flyback converters operate at the same switching frequency. However, the switches of these paralleled converters are sequenced to turn on with a half-time period compared to each others. Advantage of this is improved current waveforms in input and output.[36]

In addition to paralleled flyback converters, inverter A also uses two LV MOS-FETs as paralleled switches in these converters. These two switches are turned simultaneously on and off. Advantage of this variation with two switches is that the voltage rating of these switches halves compared to single-switch version.[36]

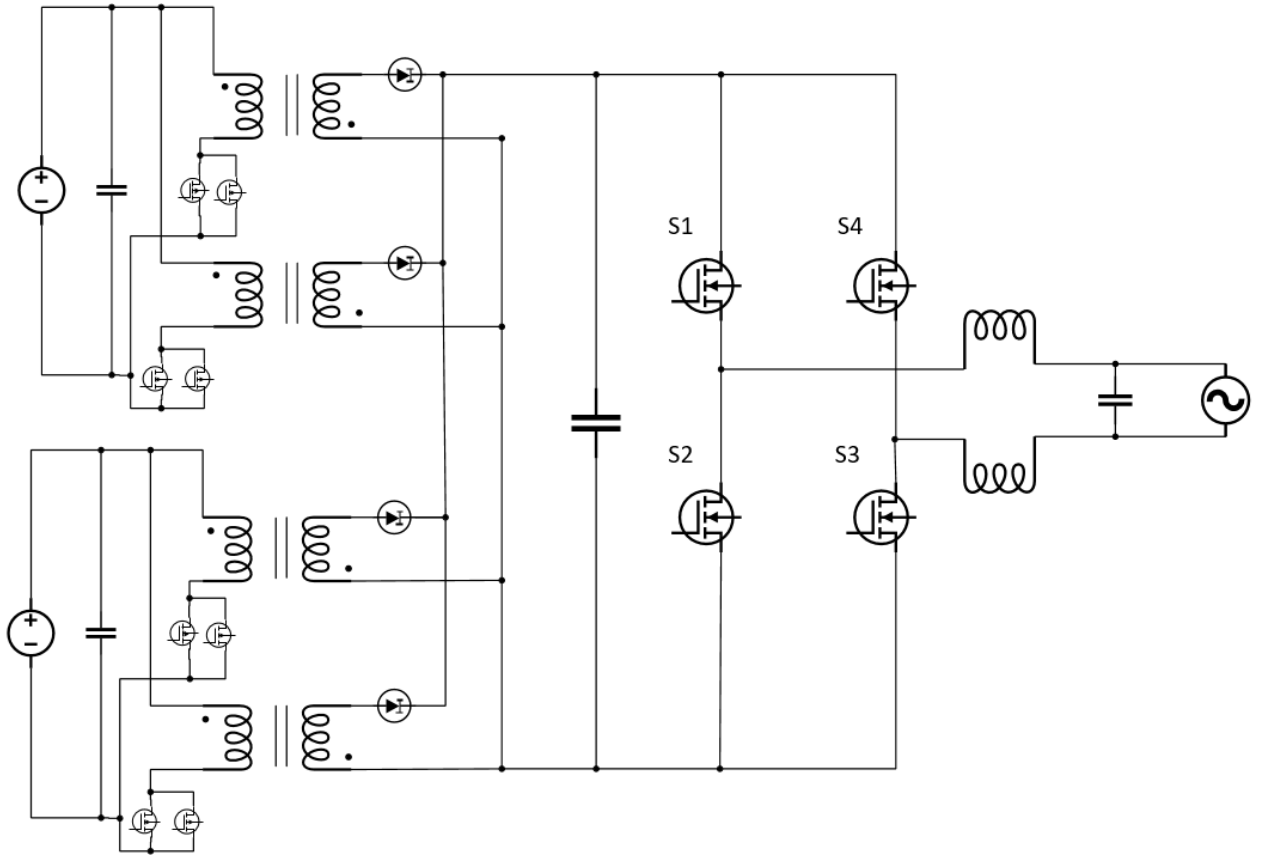


Figure 35: Schematic of inverter A.

3.2 Micro Inverter B

Inverter B, after housing is removed, is presented in Figure 36. As can be seen, inverter B was completely filled with soft foam, unlike inverter A, where only components were covered. Like in case of inverter A, foam is assumed to operate as heat dissipator and mechanical protection. Figure 37 shows the PCB of inverter B when foam is removed. Figures 36 and 37 show, that the layout of inverter B is designed in a way, that size of the housing is optimized.



Figure 36: Inverter B when housing is removed.

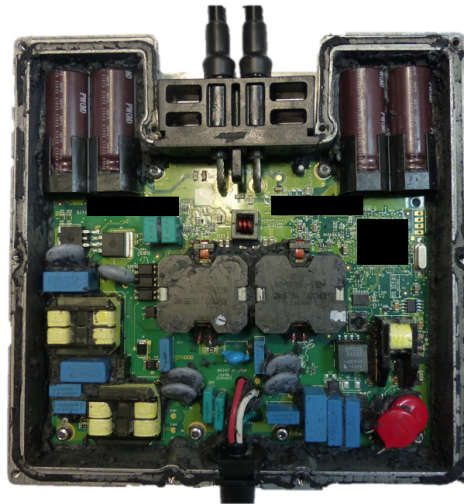


Figure 37: Inverter B when housing and soft foam are removed.

As Figure 38 shows, micro inverter B has one input channel. After it the common mode filter inductor follows. It limits the possible short circuited current. As inverter A, also inverter B has four electrolytic capacitors for compensating the power ripple

and storing energy. The difference is, that inverter B has the electrolytic capacitors on the primary side, when inverter A has them on the secondary side. LV switches, which are MOSFETs, are boosting up the voltage and tracking the MPP according to the feedback of the control loop. These switches can be seen in Figure 39. They are connected parallel with each others and each source is connected to the minus channel of the input. After LV switches, two paralleled Flyback converters are providing galvanic isolation.

Instead of conventional H-bridge, that consists of four similar semiconductor switches, in inverter B the inversion from DC to AC is done by a H-bridge, that has two MOSFETs and two thyristors as switches. Thyristors are shown in Figure 39. Upper switches, S1 and S4, are thyristors and S2 and S3 are MOSFETs. The useage of thyristors can be explained cost wise. Since the output frequency is 50 Hz, the switches can function with low switching frequency, so thyristors can be used. Nevertheless, thyristors cannot be switched off, as Section 2.8.2 explains, so MOSFETs as lower switches are needed for switching. Since thyristors are significantly cheaper than MOSFETs, it makes sense to use both MOSFETs and thyristors, even though buying bigger shipments of one product makes sense until certain point. Thyristors switch in this case at grid frequency, which is 50 Hz, and MOSFETs switch under some kHz. So using more MOSFETs than needed would be waste of money.[37]

In addition to these four switches explained before, inverter B has an fifth switch, which is an IGBT, shown in Figure 39. The purpose of this switch is to disconnect the panel from the inversion state on zero switching state, which suppresses leakage current. So inverter B uses a H5-topology, which is more carefully explained in Section 2.6.2. Anyway the reason of using this fifth switch is not fully clear, since inverter B has Flyback converters for providing galvanic isolation. As Section 3.4 and further 4.2 of this thesis will later show, also inverter D has fifth switch in its inversion-state. Anyway, capturing waveforms showed, that this switch is actually not switching, but only supposedly using its bodydiode. So it could also be one possible scenario of this circuit.

After inversion, coils and capacitors smoothen the PWM voltage to a pure sinusoidal waveform and also filter the EMI and store energy. Also in inverter B, AC current is measured, so it matches with the grid in phase and amplitude. MOVs protect the device from the possible failures in the grid. Microcontroller is naturally also part of inverter B and its function is explained in Section 3.1.

In the datasheet, the output power of inverter B is presented as Watts (W), which signifies that inverter B only provides active power, since W is the unit of active power. Equation of active power is shown in Equation (8)

$$P = U \cdot I \cdot \cos(\phi) \quad (8)$$

where U stays for AC-voltage, I for AC-current and $\cos(\phi)$ for PF.

As inverter A, also inverter B uses paralleled flyback converters with two paralleled LV MOSFETs as switches. Figure 40 represents this. These variations of flyback converter, explained in Section 2.6.4, are explained in Section 3.1.

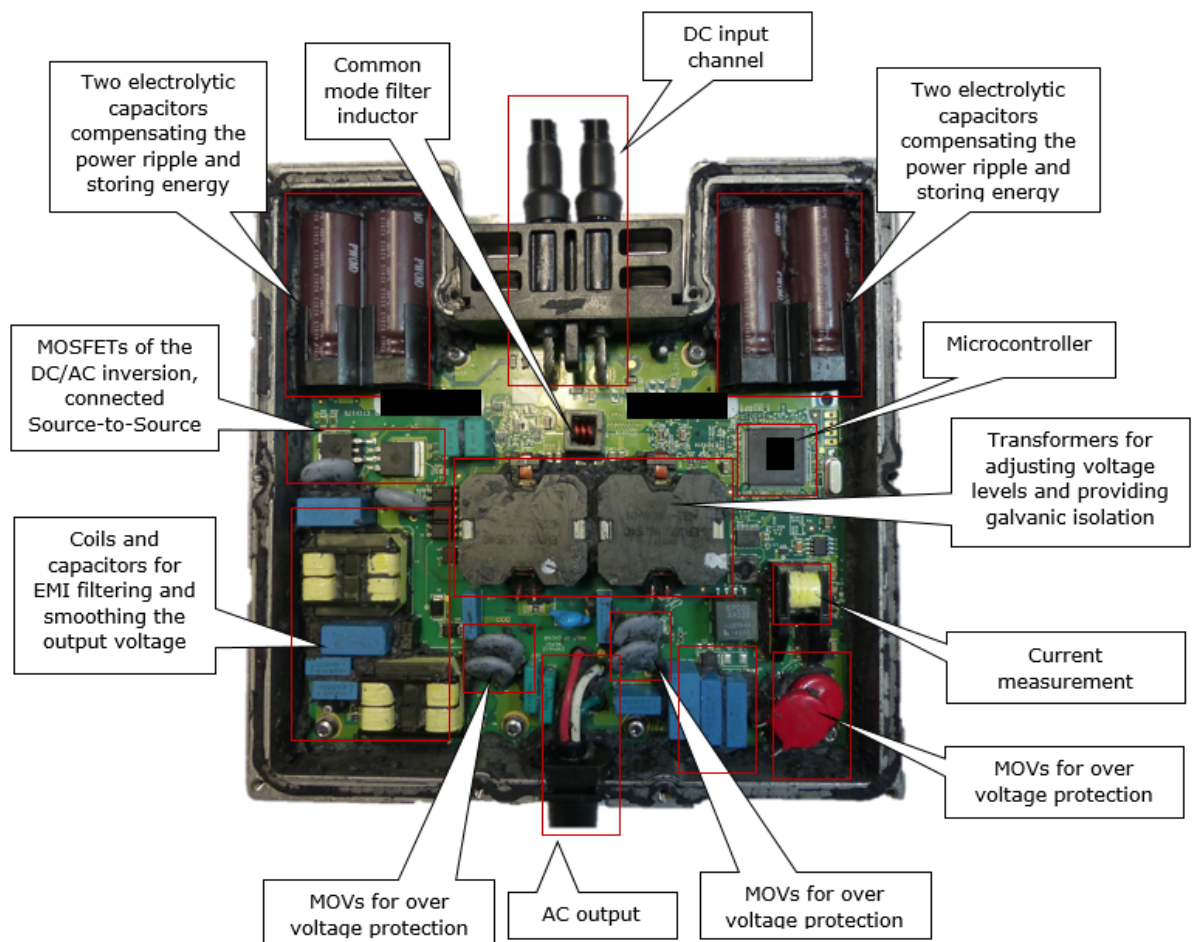


Figure 38: Inverter B with clarifications.

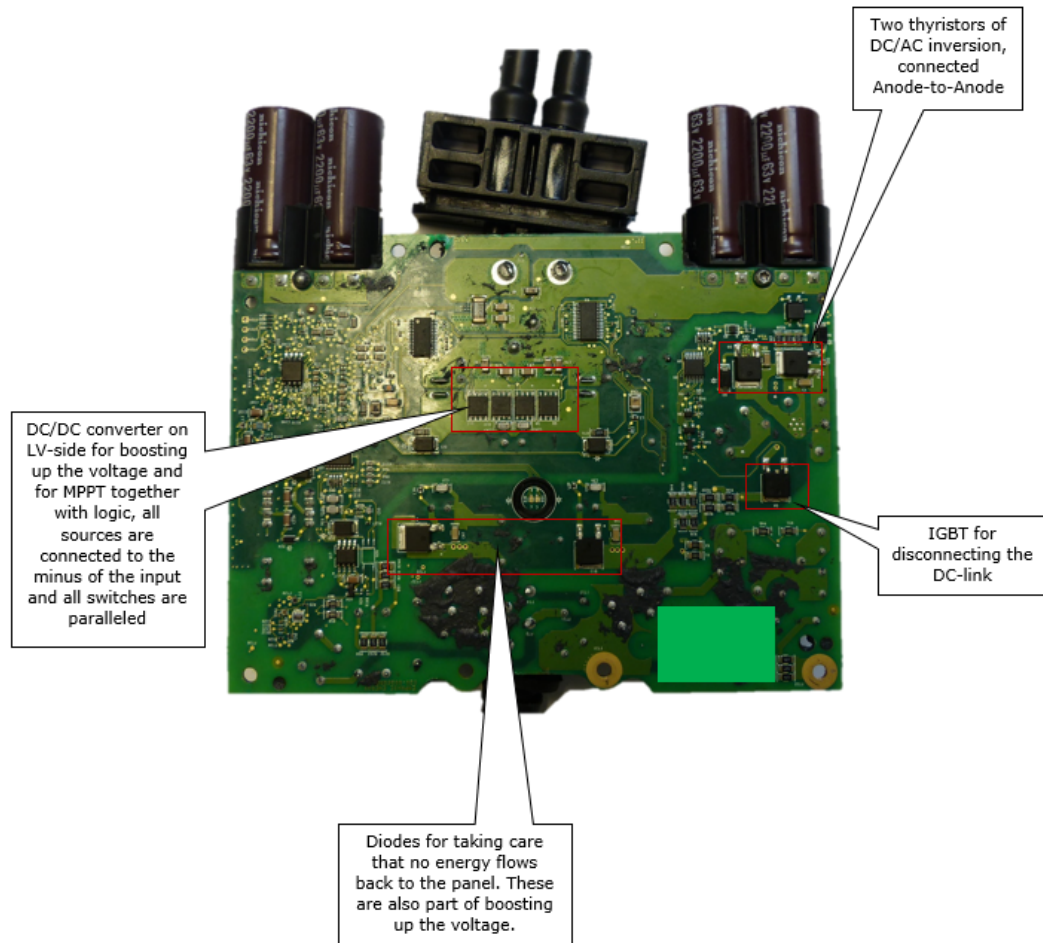


Figure 39: Back side of inverter B with clarifications.

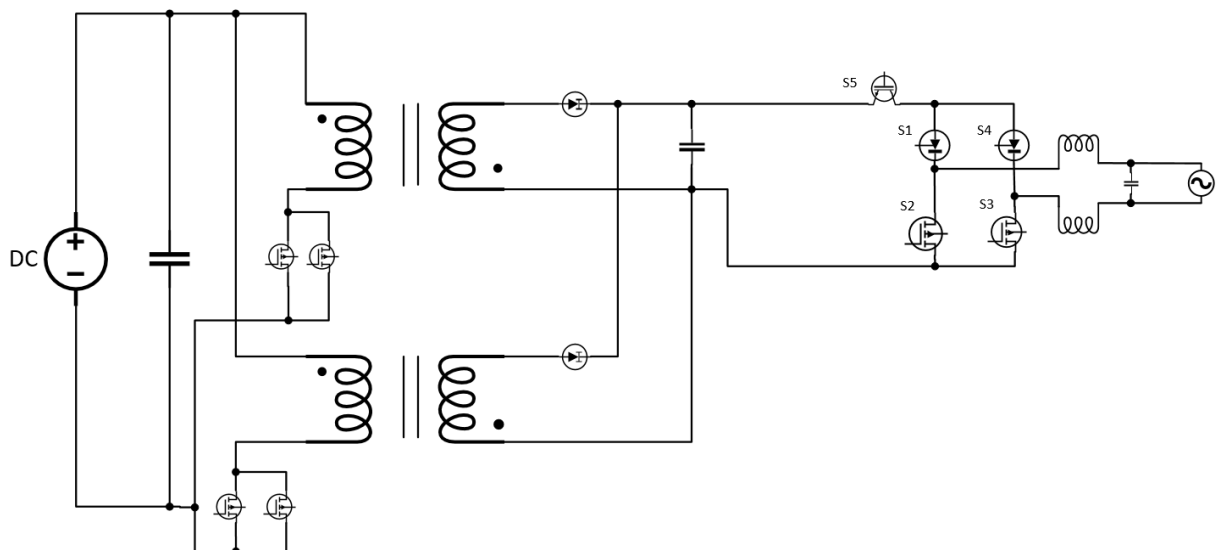


Figure 40: Schematic of inverter B.

3.3 Micro Inverter C

Inverter C is represented in Figures 41 and 42 with and without soft foam, respectively. Like in case of inverter A and B, also in inverter C the foam is assumed to operate as heat dissipator and mechanical protection. As in case of inverter B, also in inverter C the shape of each component has been taken into account when designing the configuration of the inverter. Figure 43 clarifies different parts of inverter C.

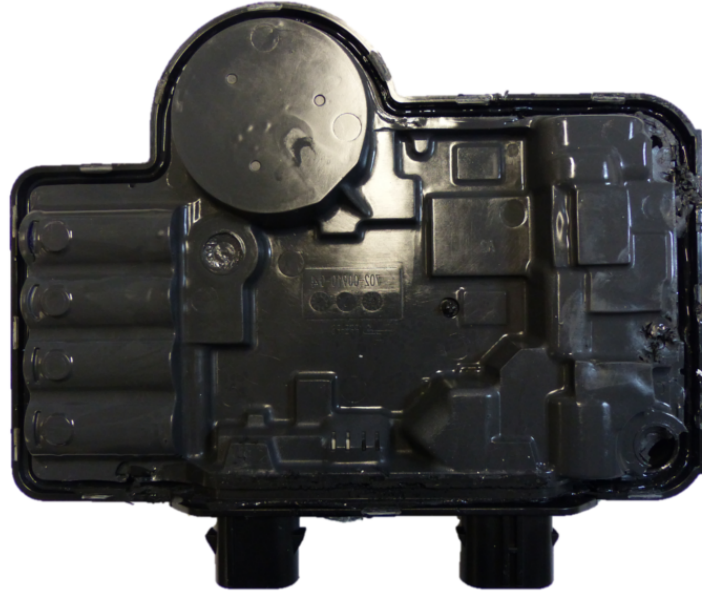


Figure 41: Inverter C when housing is removed.

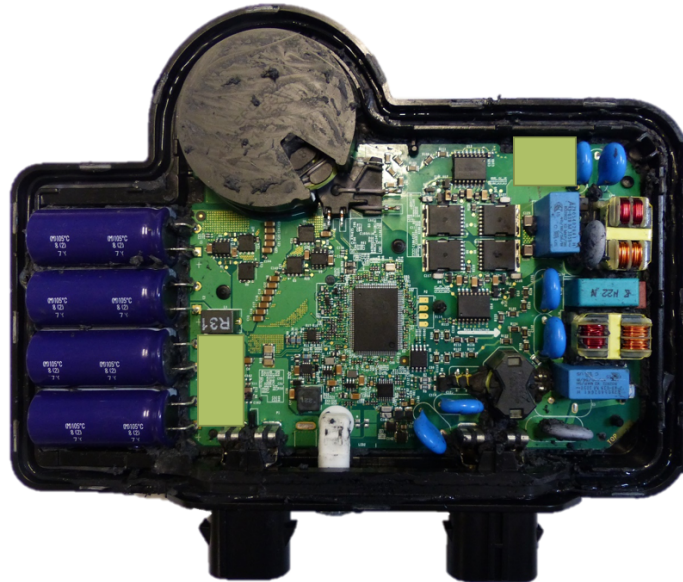


Figure 42: Inverter C when housing is removed.

As inverter B, also inverter C has only one input channel. This can be seen in Figure 43. After input and before the transformer, four electrolytic capacitors are placed. As in inverters before, also here, they compensate the power ripple and store energy. Transformer provides galvanic isolation and LV MOSFETs provide MPPT and boost up the voltage for needed level. After voltage is boosted up, a cyclo converter, explained in Section 2.6.3, does the DC/AC inversion. MOSFETs in cyclo converter are controlled by gate drivers. PWM voltage, that is produced in inverter, is smoothened by coils and capacitors, which also provides EMI filtering. Also in inverter C, AC current is measured, like explained in Sections 3.1- 3.2. Microcontroller controls the device and MOV is protecting the device from grid failures, as also explained in previous sections.

PWM voltage, that is produced in inverter, is smoothened by coils and capacitors, which also provides EMI filtering. Also in inverter C, AC current is measured, like explained in Sections 3.1- 3.2. Microcontroller controls the device and MOV is protecting the device from grid failures, as also explained in previous sections.

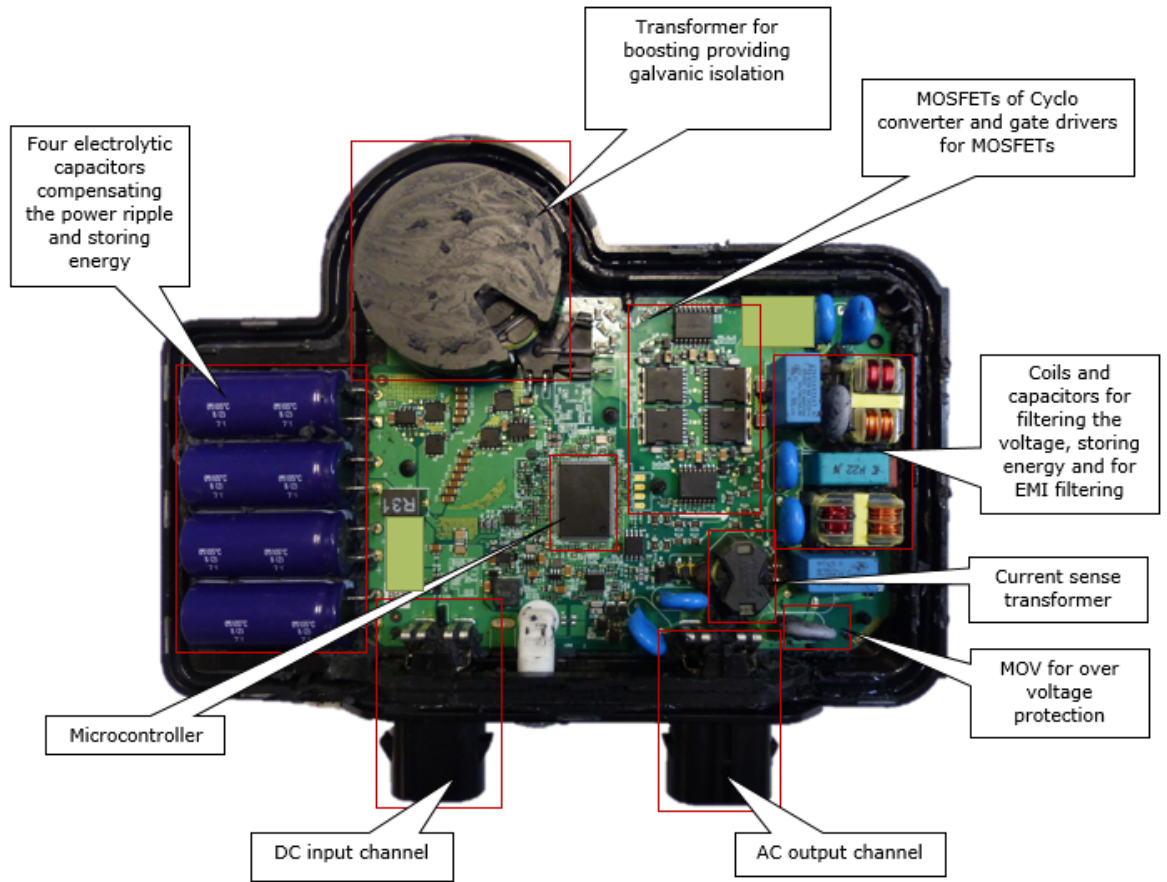


Figure 43: Inverter C with clarifications.

Like the datasheet of inverter A, also the datasheet of inverter C provides output power in unit of VA. This signifies that also inverter C provides both active and reactive power, as shown in Equation (7).

As schematic of inverter C in Figure 44 shows, the DC/AC inversion is done with cyclo converter, clarified in Section 2.6.3. Inverter C uses only a single transformer for galvanic isolation.

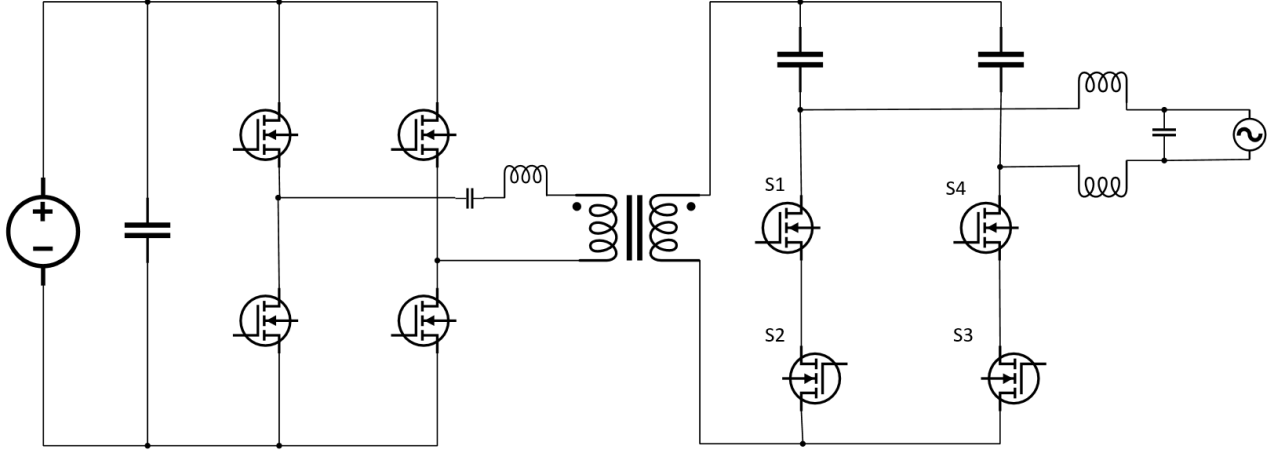


Figure 44: Schematic of inverter C.

3.4 Micro Inverter D

Inverter D is represented in Figure 45, when housing is removed but soft foam is left. Inverter D, when soft foam is removed, is shown in Figure 46. Like in case of inverter A, B and C, also in inverter D the foam is assumed to operate as heat dissipator and mechanical protection. Foam of inverter D has lots of cavities as Figure 45 shows.

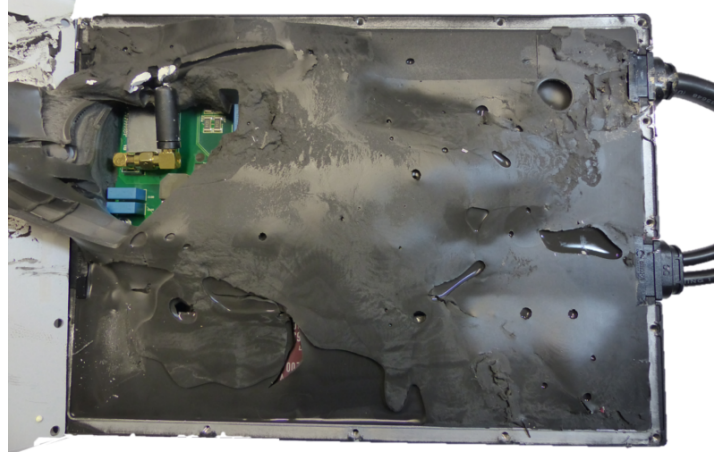


Figure 45: Inverter D when housing is removed.

Inverter D has two input channels, like inverter A. Additionally it has two AC terminals, which enables the installation of solar panels in a chain. On the DC link, in total ten electrolytic capacitors are compensating the power ripple and storing energy.

As Figures 47 and 48 represent, capacitors, flyback converters and LV semiconductor switches are independent for each input channel. Each channel has five capacitors, two flyback converters and four LV switches. Flyback converters provide galvanic isolation and LV switches boost up the voltage and provides MPPT.

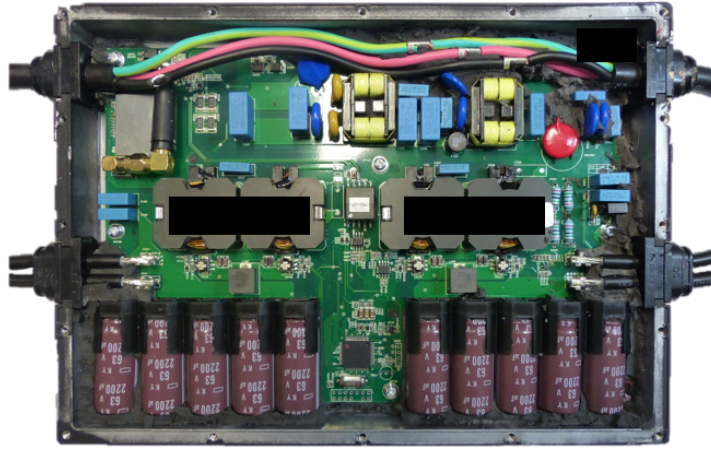


Figure 46: Inverter D when housing and foam are removed.

After boosting, the DC/AC inversion occurs. It is operated with five switches: three MOSFETs and two thyristors. The reason behind usage of thyristors is explained in the Section 3.3. Thyristors are the upper switches, so called S1 and S4, like in inverter B. The fifth MOSFET is connected to the sources of MOSFETs and its purpose is to disconnect the panels during the zero switching voltage. This is, as in case of inverter B, H5-topology and it is clarified in Section 2.6.2.

After inversion the voltage is smoothened and EMI is filtered with coils and capacitors. These also participates to energy storing. Varistor before AC output protects the device from failures, for example lightning strikes, in the grid. The AC current is also in inverter D measured, so it matches in phase and amplitude with the utility.

Inverter D uses wireless communication for monitoring the solar plant data, alarming about failures and detecting possible operational failures as soon as possible.[48] As a difference from inverter A, which also uses wireless communication, can be noticed, that in case of inverter D, the antenna is located inside of the housing. Microcontroller is an integrated circuit that consists of central processing unit (CPU), memory devices, timers, counters etc.[47]

The datasheet of inverter D provides output power as watts, which indicates that it provides only active power to utility. Equation (8) provides an explanation for this.

As inverter A and C, also inverter D uses paralleled flyback converters with two paralleled MOSFETs as switches. Figure 40 represents this. These variations of flyback converter, explained in Section 2.6.4, are explained in Section 3.1.

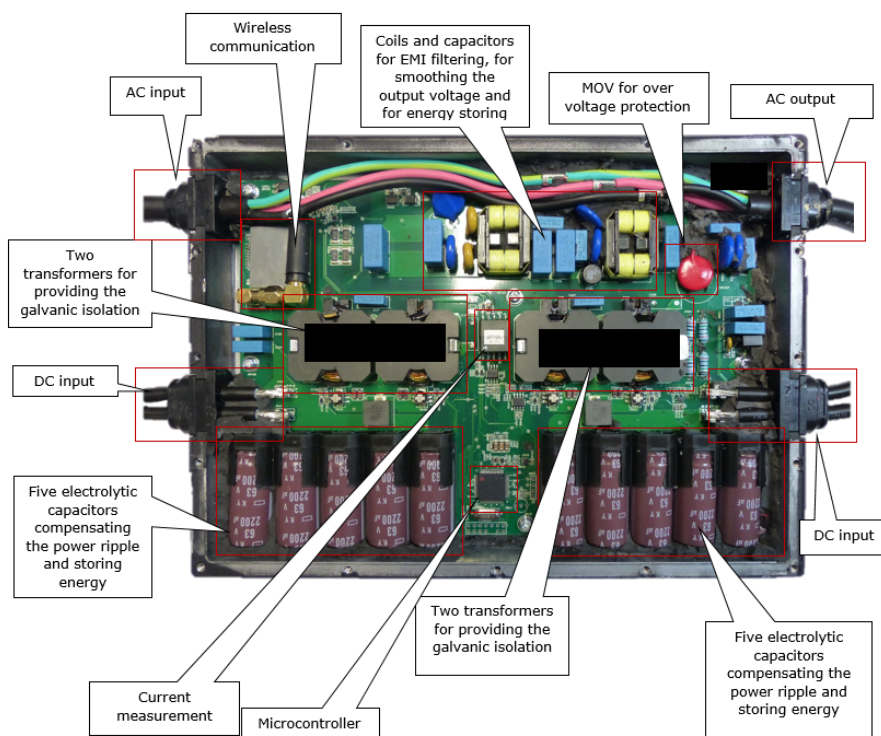


Figure 47: Upper side of inverter D with clarifications.

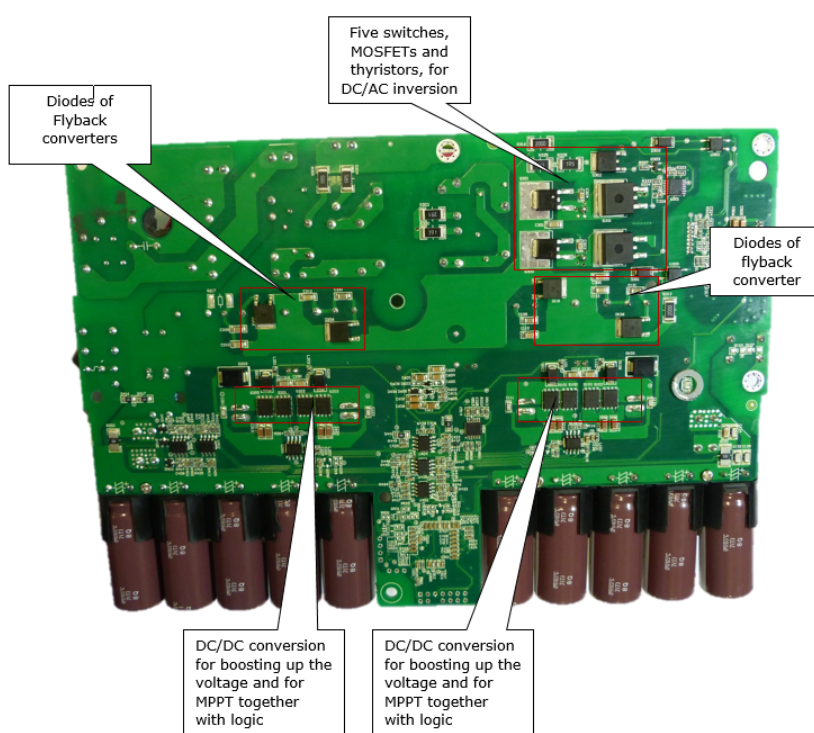


Figure 48: Down side of inverter D with clarifications.

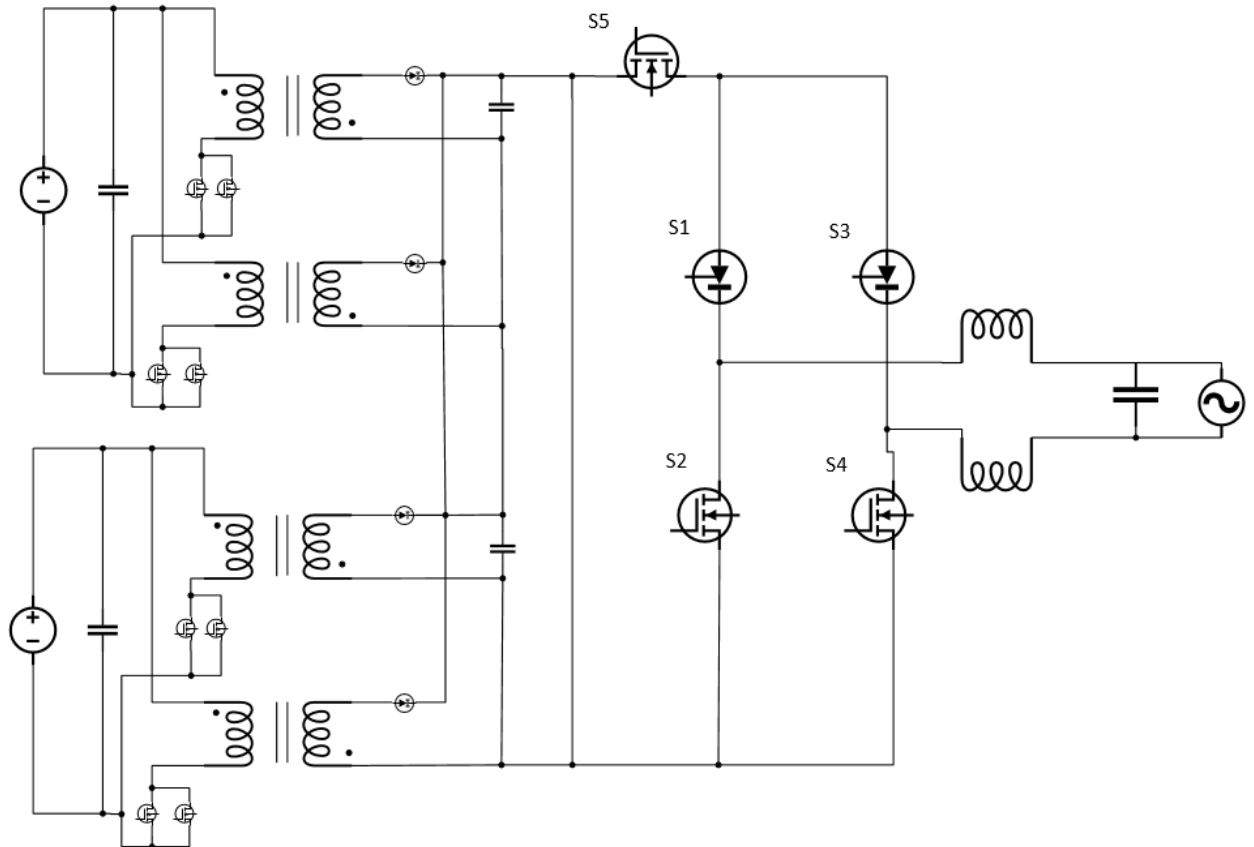


Figure 49: Schematic of inverter D.

3.5 Inverter Comparison

This Section provides a comparison between the inverters A, B, C, and D introduced in Section 3.1- 3.4. Table 3 summaries the main differences between inverters A-D.

Table 3: Basic characteristic comparison

Inverter	DC input channels	AC Input channels	Feeds Q	Wireless
A	2	-	Yes	Yes
B	1	-	No	No
C	1	-	Yes	No
D	2	1	No	Yes

As Table 3 shows, two of the reverse engineered inverters have two DC input channels, and two of them has only one. Inverter D has in addition to two DC input channels also one AC input channel. Inverter A has only AC output, but also two DC input channels. This effects on the installation of micro inverter.

During the tear down an assumption was made, that when the datasheet of an inverter provides output power as W, the inverter supplies only active power (P) and when the output power is given in VA, the inverter feeds both reactive (Q) and active power to utility. From the teared down inverters only two, inverter A and D, has an output power in the unit of VA in their datasheets, which makes them more interesting for the market compared to the ones, who cannot compensate reactive power.

Two of the inverters have wireless communication and in case of inverter D the antenna is located inside of the inverter. In inverter A the antenna is located outside of the housing. Inverter B and C do not have wireless communication and in their case communication happens via AC output cable.

3.5.1 Size

Table 4 shows the dimensions and weight of each reverse engineered inverter. Inverter A is the biggest, but D is the heaviest. Nevertheless the differences are not big. One thing anyway can be concluded: inverter with two channels are bigger than inverter with one channel. This naturally makes sense, since more terminals and more and bigger components inside are needed.

3.5.2 Electrical Values

Tables 5 and 6 compares electrical values and performance of inverters A-D. Dash indicates the lack of information in the datasheet.

Efficiencies, told in the datasheets, does not differ majorly from each others. Also values fot PF are all quite similar. Lowest one is in inverter B. Inverter C is the only

Table 4: Size comparison

Inverter	Width(cm)	Height(cm)	Depth(cm)	Weight(cm)
A	26	18.8	3.15	2.6
B	17.1	17.3	3	1.6
C	21.2	17.5	3.02	1.08
D	25	17	2.8	3

Table 5: Comparison of electrical values

Inverter	V_{in} (V)	V_{out} (V)	I_{in} (A)	I_{out} (A)	P_{out}	V_{MPP} (V)
A	60	230	12x2	2.39	550 VA	22-45
B	48	240	-	0.9	215 W	27-39
C	60	230	-	1.26	290 VA	27-45
D	60	240	11.5	2.5	600 W	29-48

inverter, which provides the information of lagging and leading. If compared to 2.7, all of the available PF and THD values are inside of the regulated limits. Inverter B and C do not provide information about THD.

Table 6: Performance comparison

Inverter	η (%)	PF	THD(%)	Temperature range
A	96.7	>0.99	<3	-40...+65°C
B	96.5	>0.95	-	-40...+65°C
C	96.5	0.85 leading...0.85 lagging	-	-40...+65°C
D	96.7	>0.99	<3	-40...+65°C

3.5.3 Used Topologies

Table 7 compares the used switches, amount of transformers and energy storing method of inverter A-D. In this table with transformer both conventional transformer and flyback converter are meant.

All of the reverse engineered inverters contain electrolytic capacitors. Inverters A-D have four of them each, but inverter D has ten. In inverters B, C, and D, electrolytic capacitors are located in the DC-link, but in case of inverter A, they are after the transformers, on the secondary side.

Table 7: Inversion topology comparison

Inverter	Switches LV	Switches HV	Transformers	Electrolytic capacitors	Topology
A	8	4	4	4	H4
B	4	5	2	4	H5
C	4	4	1	4	Cyclo converter
D	8	5	4	10	H5

$$W = \frac{1}{2} \cdot C \cdot U^2 \quad (9)$$

As Equation (9) shows, the bigger the voltage is, also the bigger is the amount of stored energy W . So when installing the electrolytic capacitors on the secondary side, where the voltage is already stepped up, also more energy can be stored.

In micro inverters A, B and D the galvanic isolation was done by flyback converter and in inverter C with a transformer. Boosting up the voltage and MPPT was provided by LV switches and with logic circuit in all inverters that were teared down.

As in Section 2.5 was explained, currently the interest is on transformerless inverter topologies. Anyway, the practical part of this thesis indicates, that at least many micro inverters are still using transformers for providing the galvanic isolation. One reason behind this could be, that since micro inverters are used in residential section, galvanic isolation is ensured with transformers to avoid any dangers of leakage current. Also with transformers, less semiconductor components are needed.

3.5.4 Heat dissipation and packaging

All of the reverse engineered inverters were filled with soft foam, as it is called in this thesis. The material of this foam is unknown, but it might be polyurethane, which is used for potting electronic components.[50]

Packaging has an important and even a self-evident role in an inverter. As mentioned before, it works for example as an heat dissipator. It also composes all components to one unit, that is easy to ship, install and maintain. Packaging protects components from external elements, like weather conditions, dirt and water and also keeps people, animals, etc. away from the equipment. In packaging the use of high quality materials, like corrosion-resistant fasteners and stainless steel screws, is necessary, so the maximum lifetime can be achieved.[4]

Packaging did not difference dramatically in reverse engineered inverters. As can be seen from the Figures 37 and 42, in case of inverter B and D the packaging is designed the way, that the form of components has been taken into account and therefore size of an inverter is optimized.

4 Measurements

Measurements for this thesis were done with the setup shown in Figure 50 and were planned to do as follows:

1. Powering up the inverter with original setup
2. Measuring electrical values and temperatures with original setup
3. Capturing waveforms of original setup
4. Replacement of semiconductor switches in secondary side
5. Powering up with replaced switches
6. Measuring electrical values and temperatures with replaced switches
7. Capturing waveforms with replaced switches

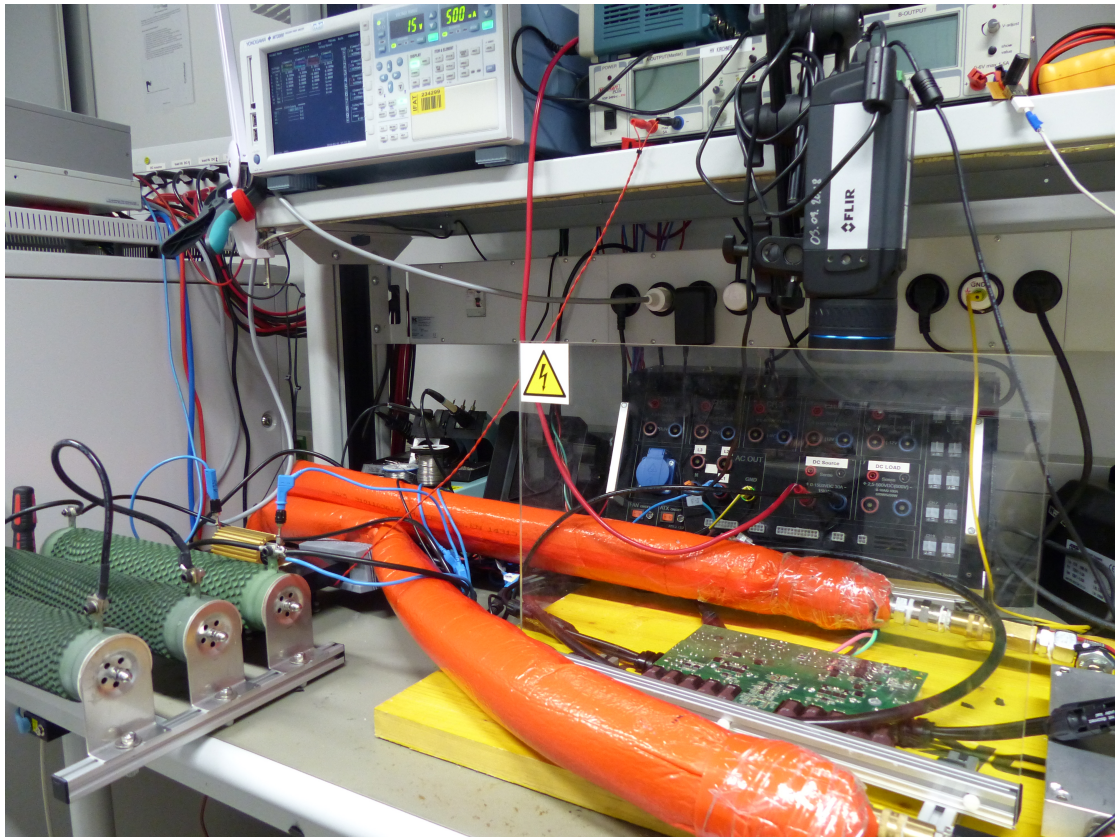


Figure 50: Measurement setup with additional resistors for decreasing the oscillation.

The idea was to replace the semiconductor switches to Infineon-devices and examine, if this has effect to temperatures or efficiency.

As Figure 50 and Figure 51 show, two resistors (4.7Ω each) were added between the DC power supplies and each input channel of micro inverter. This procedure was

done to decrease the oscillation, which occurred since the MPPT of micro inverter was working against the power supply. This can be explained by the different IV-curves of solar panels and DC power supplies. Oscillation was seen in the control of supplies, since they were switching rapidly between constant current and constant voltage modes. With resistors the supplies were able to be kept in constant voltage mode. With this setup the voltage was changed in the supply during measurements and current was adjusted automatically by the voltage.

The first round of measurements were done with original setup. During the measurements the inverter was powered up with full power for 60 minutes. After that, measurements were done in ten minutes periods. Input current, output current, input voltage, output voltage and maximum temperature were measured at twenty percent intervals. Efficiency, output power and input power were calculated as Equation (10) shows.

$$\eta = 100\% \cdot \frac{P_{OUT}}{P_{IN}} = 100\% \cdot \frac{V_{OUT} \cdot I_{OUT}}{V_{IN} \cdot I_{IN}} \quad (10)$$

After measuring the electrical values mentioned before, waveforms of MOSFETs' gate signal, drain-to-source voltage and output voltage were captured. This was repeated two times to be sure of the validity of values. After measuring with original setup, semiconductor components were replaced with Infineon's components, if possible.

Devices, that were used in measurements, are listed below:

- Chroma Programmable DC Power Supply 62024P-600-8
- EA Power Supply EA-PS 81500-30 15000W
- Power Analyzer YOKOGAWA WT3000
- Grid Emulator Cinergia GE-30
- Infrared Camera FLIR A655sc
- Digital Phosphor Oscilloscope DPO7354

In the measurements, inverter was feeded by two separate DC power supplies instead of solar panels. Reasons behind this was time limits, simplicity and cost. Power analyzer was used for measuring the electrical values and it was connected between power supply and inverter. Because of Austrian regulations, inverter could not be connected directly to the utility grid, so grid emulator was used. Schematic of the measurement setup is represented in Figure 51. As schematic shows, since two DC power supplies were used, also two channels (1 and 4) of power analyzer were used for input. Channel 3 was used for output.

Thermal behaviour of the semiconductor components was monitored with a thermal camera and waveforms were captured with an oscilloscope. Figure 52 shows how the temperatures were measured with the thermal camera. The maximum temperature of each component was measured separately with FLIR tools -software.

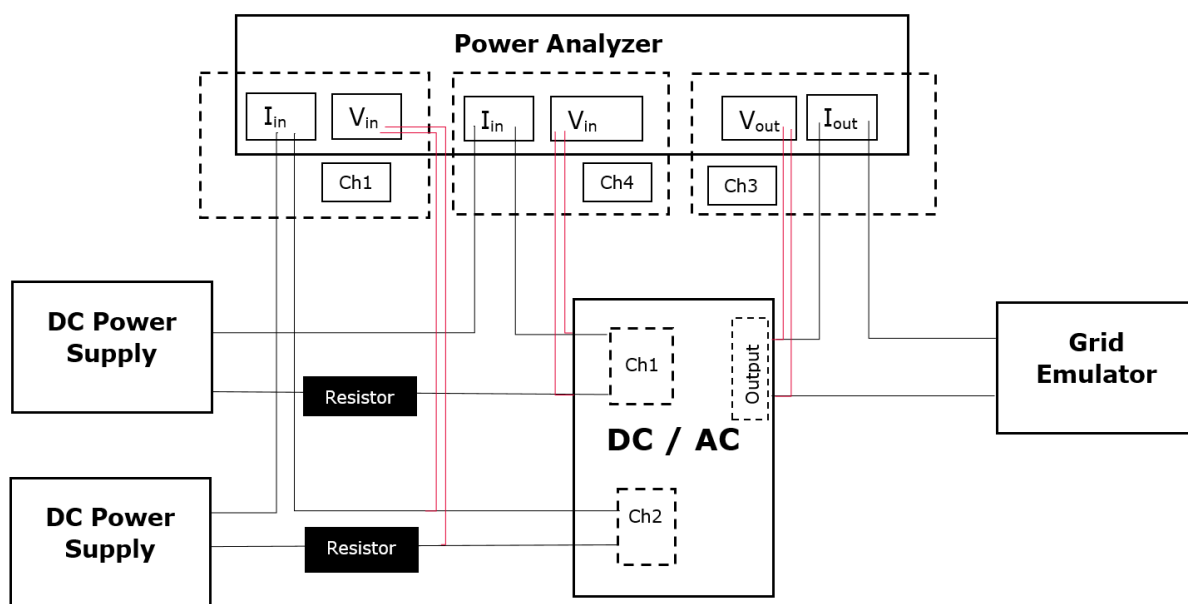


Figure 51: Schematic of the measurement setup. Ch1 stands for channel one, Ch2 for channel two, Ch3 for channel 3 and Ch4 for channel four. The channel 2 of power analyzer was not used. Red lines represents the wires for voltage sensing and black lines represent the cables.

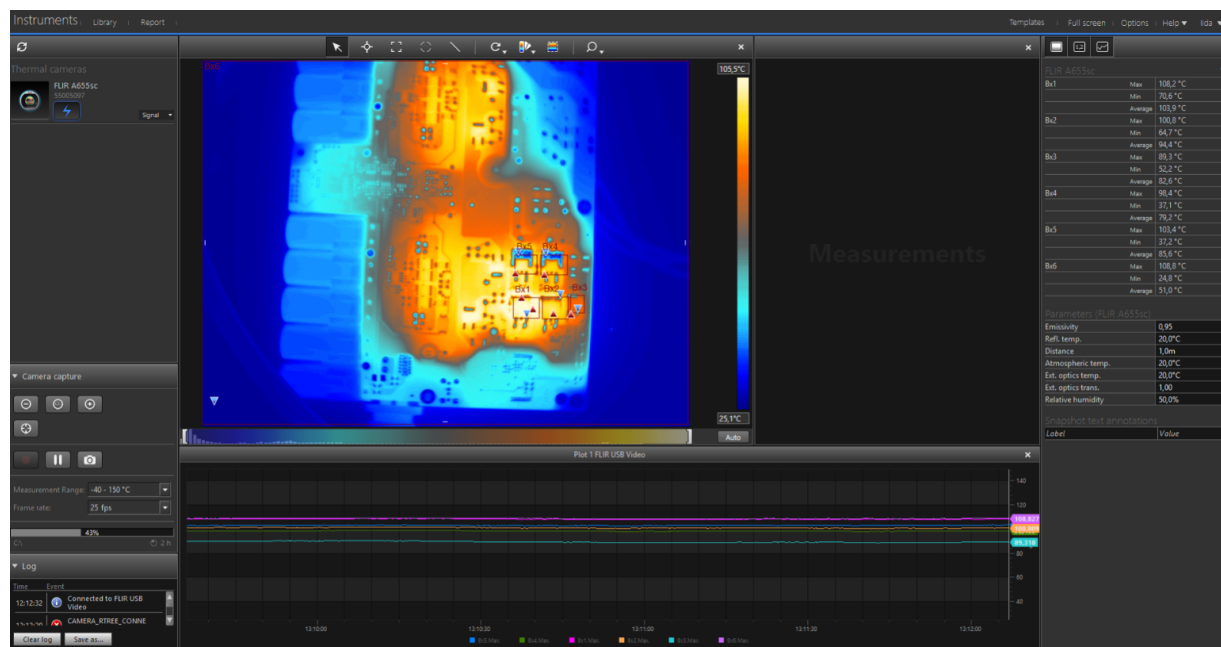


Figure 52: Measuring the temperatures of different components.

4.1 Measurement of Inverter A

Measurements for inverter A were done with closed housing and the black foam was attached. Only a small hole was sawed to the housing and the foam was removed around the HV switches, so thermal measurements could be done and switches could be changed.

Efficiency and temperatures were measured in five different points, shown in Table 8. Highest power, that was reached, was 600 W and other points were calculated from this maximum value. Measurements were done in 20 % intervals. In total three measurement rounds were done: first with original setup, then with MOSFETs with $R_{DS(ON)} = 145 \text{ m}\Omega$ and lastly with $R_{DS(ON)} = 170 \text{ m}\Omega$. Table 9 represents the MOSFETs used in measurements.

Table 8: Measurement intervals of output power levels

Percentage	Output Power
100 %	600 W
80 %	480 W
60 %	360 W
40 %	240 W
20 %	120 W

Table 9: Used semiconductor components in different measurement rounds

Setup	S1	S2	S3	S4
1.	STB33N60DM2	OSG60R108KZ	OSG60R108KZ	STB33N60DM2
2.	IPB60R145CFD7	IPB60R145CFD7	IPB60R145CFD7	IPB60R145CFD7
3.	IPB60R170CFD7	IPB60R170CFD7	IPB60R170CFD7	IPB60R170CFD7

Efficiency curves of inverter A are represented in Figure 53. Blue curve represents the efficiency at different power levels when original switch setup was used. Orange curve as for represents the efficiency curve when MOSFETs with $R_{DS(ON)} = 145 \text{ m}\Omega$

were used as switches and grey curve shows the efficiencies at different power levels when MOSFETs with $R_{DS(ON)} = 170 \text{ m}\Omega$ was used.

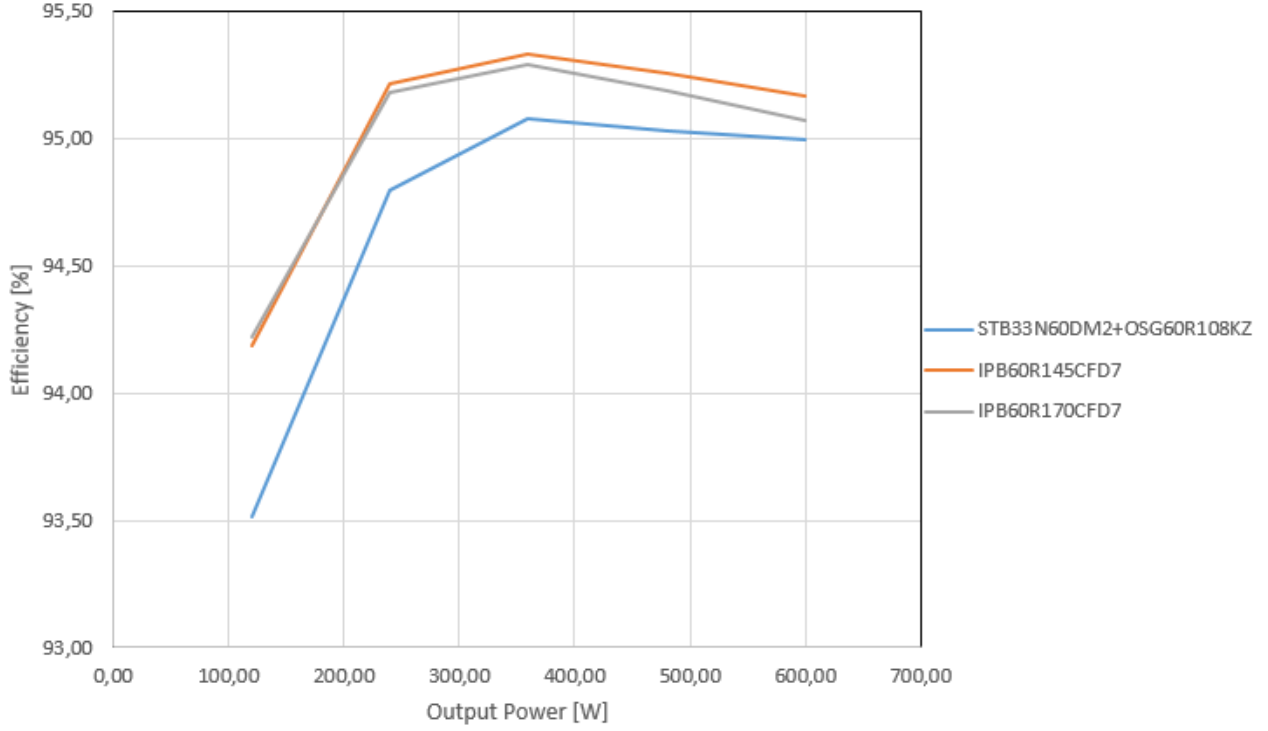


Figure 53: Efficiency curves of inverter A.

As Figure 53 shows, the lowest efficiency was reached with the original setup and the highest efficiency was reached with the switches with $R_{DS(ON)} = 145 \text{ m}\Omega$. On the lowest measured power level (120 W) efficiency of the inverter was slightly highest with the MOSFETs with $R_{DS(ON)} = 170 \text{ m}\Omega$ and then on the highest measured power level (600W) efficiency of the inverter was highest with the MOSFETs with $R_{DS(ON)} = 145 \text{ m}\Omega$. This makes sense, since with the lower $R_{DS(ON)}$ the better performance on higher power levels will be reached, because lower $R_{DS(ON)}$ decreases the conduction losses. This is clarified with Equation (11).

$$P_{cond} = R_{DS(ON)} \cdot I_D^2 \quad (11)$$

where P_{cond} stands for conduction losses, $R_{DS(ON)}$ for drain-to-source resistance on on-state and I_D for drain current.

With higher $R_{DS(ON)}$ then again the parasitic capacitances are lower due to the smaller chip-sizes, what is reflected in the lower switching losses. This phenomenon can be seen at the lower power levels, where less current is flowing through MOSFETs, what significantly lower conduction losses, as shown in Equation (11). In this condition switching losses dominate over conduction losses.

Figure 54 represents the measured temperatures of each measurement round. Only temperatures at 100 % load are shown, since this is when the temperatures naturally are the highest and the most critical. As Figure 54 shows, the temperatures

of S1 and S3 are higher than the temperatures of S2 and S4. Can be verified, that the reason is their location. S1 and S3 are located physically closer to flyback converters on the PCB than S2 and S4. Since these converters dissipates lots of heat, is also the ambient temperature of switches, located close, higher.

When comparing the temperatures of different setups, can be seen, that the temperatures of original setup (blue pillars) are the highest. This aligns well with the fact, that the efficiency with the original setup was the lowest (Figure 53). This is due the fact, that losses appears as heat. When comparing the orange and the grey pillars, can be seen, that the temperatures of lower $R_{DS(ON)}$ are lower. This can be explained with Equation (11), since conduction losses increase when resistance increases.

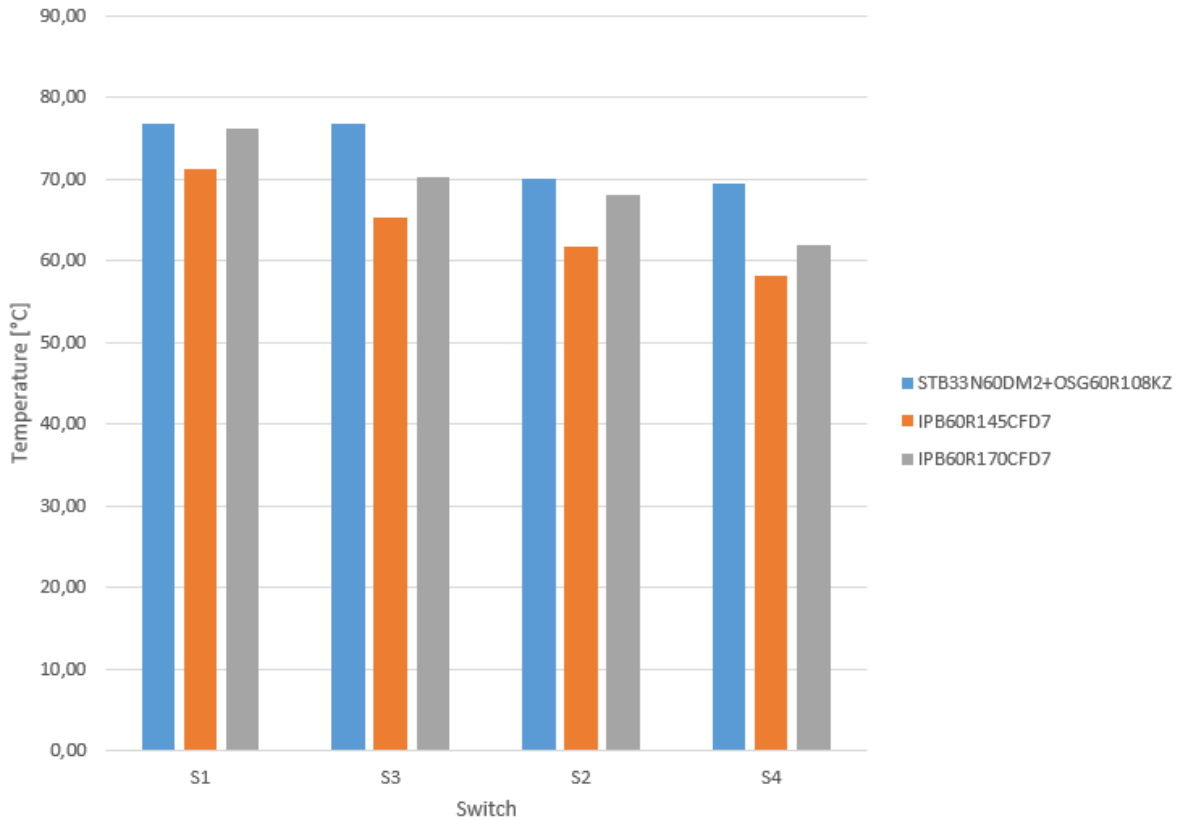


Figure 54: Temperatures of each measurement round of each switch in case of Inverter A. Only temperatures at 100% are shown, since that is when the temperature is the highest.

Captured waveform of inverter A is shown in Figure 55. This capture of waveforms is chosen to be presented, since it shows how the transition mode between alternatively switching switches happen. This Figure is zoomed in, so transition mode can be easily seen. With transition mode the moment is meant, when two diagonal switches are open and after certain dead-time, which is needed for capacitors and coils in the circuit to loose their charge, other diagonal switches close.

As explained in Section 2.6.1, other half of the switches in full-bridge configuration

are switching with grid frequency and other half is switching with high frequency. This can also be seen in Figure 55: yellow waveform shows gate-signal of the low-side switch. After certain spot, gate-signal is zero and then this earlier mentioned dead time occurs. After dead-time, high-side switch (green waveform in the Figure), starts to switch with high frequency. What has to be noticed here is, that only one leg of the bridge was captured, so that's why the diagonal switch with low frequency, cannot be seen.



Figure 55: Zoom of captured waveforms of inverter A. Green stands for V_{DS} of upper switch and blue for V_{DS} of lower switch. Yellow stands for the gate-signal of lower switch and purple for the gate-signal of higher switch. .

4.2 Measurements of Inverter D

As explained in Section 4, measurements were done in intervals of twenty percentage. These power levels are shown in Table 10. Percentages are calculated from this measured maximum. As Section 3.4 explains, inverter D has three MOSFETs and two thyristors.

Maximum output power that was reached was 515 W, although datasheet of the inverter D claimed it to be 600 W. The maximum power was reached by increasing the output power of the power supply slowly until it switched itself off. When trying to feed the inverter with higher power, it went to thermal protection after 20 minutes of running.

Measurements for inverter D were done with open housing and without black foam. This was needed, since the switches were located on the back side of the PCB, so the inverter had to be taken away from the housing. Once the foam is removed, it is neraly impossible to attach back, so measurements were done without. However, measuring without housing effects to efficiency descending. This is because housing provides better cooling for the inverter, as it functions also as a heat sink.

Since the waveforms did not have major differences with different switch selection, waveforms are only represented once in this thesis.

Table 10: Measurement intervals of output power levels

Percentage	Output Power
100 %	515 W
80 %	412 W
60 %	309 W
40 %	206 W
20 %	103 W

Inverter D was measured with three different setups: first with original switches, then two switches, in positions S2 and S3, were replaced with MOSFETs with $R_{DS(ON)} = 280 \text{ m}\Omega$ and lastly also S5 was replaced to a MOSFET with $R_{DS(ON)} = 600 \text{ m}\Omega$.

Since the upper switches of the H-bridge, i.e. S1 and S4, are thyristors, only lower switches, S2, S3 and S5 could have been changed. Reason behind this is that there are no thyristors in the selection of Infineon. Thyristors were not able to be changed by MOSFETs, due to the conduction paths in the PCB: Gate and drain of switches would have been connected together which naturally would have not been worked out.

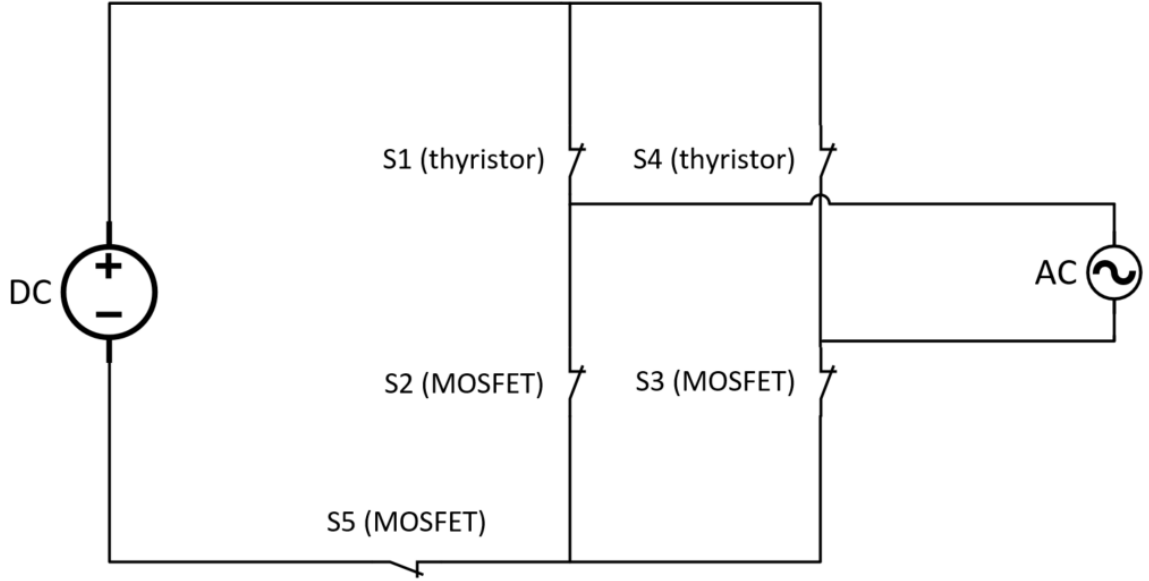


Figure 56: Switches of inverter D.

The components, used in each measurement round, are represented in Table 8. Due to privacy, only components of Infineon are told.

Table 11: Used semiconductor components in measurement rounds.

Setup	S1	S2	S3	S4	S5
1.	Thyristor	SPB17N80C3	SPB17N80C3	Thyristor	STD10NM65N
2.	Thyristor	IPD80R280P7	IPD80R280P7	Thyristor	STD10NM65N
3.	Thyristor	IPD80R280P7	IPD80R280P7	Thyristor	IPD80R600P7S

First round of measurements were done with the original setup. Figures 57 - 60 show the waveforms of original setup. 57 and 58 show the waveforms of H-bridge and 60 shows the waveforms of the fifth switch.

As green waveform from channel 4 in Figure 57 and 58 show, output voltage of the inverter D is pure sinusoidal wave. The yellow wave shows the gate-signal of the S2 and it represents how the switch is switching itself on and off. Blue and purple waves are the V_{DS} of the S2 and S3. They show, how the switching happens alternately.



Figure 57: Waveforms of H-bridge original setup. Yellow stands for gate-signal, blue and purple for V_{DS} and green for V_{OUT} .

As Figure 57 shows, after the inversion the current is actually rectified and voltages never go to negative side. This means, that inverter D is basically a single-stage inverter with polarity check. Sinusoidal wave is generated by changing the polarity alternately. This is clarified in Figure 59.

As Figure 60 shows, the yellow waveform is staying stable, which means, that the fifth switch is actually not switching. Instead of switching, it is working as a diode, using only the body diode of the MOSFET. This came as a surprise and means, that topology used in inverter D is not H5 as thought, but conventional H4. One possible reason for this additional switch could be protection: it could enable the inverter to be disconnected from the panels, if needed.

As Figure 61 shows, replacing the switches in inverter D, made a difference in efficiency. Nevertheless, when also fifth switch was replaced, the efficiency remained almost the same. But since it is not actually switching, like concluded during capturing the waveforms, can be assumed, that this fifth switch does not have so much effect to the efficiency, since it does not have switching losses at all.

Figure 62 represents the measured temperatures of switches in case of inverter D. As Figure shows, the thyristors (S1 and S4) have slightly lower temperatures compared to MOSFETs in the H-bridge. Nevertheless the temperatures of thyristors are aligned, which is expected, since they were not replaced during measurements.

Switch S5 has the lowest temperature, before the switch is replaced. Anyway, has to be noticed, that the temperature of S5 increases, even before replacing it. Reason

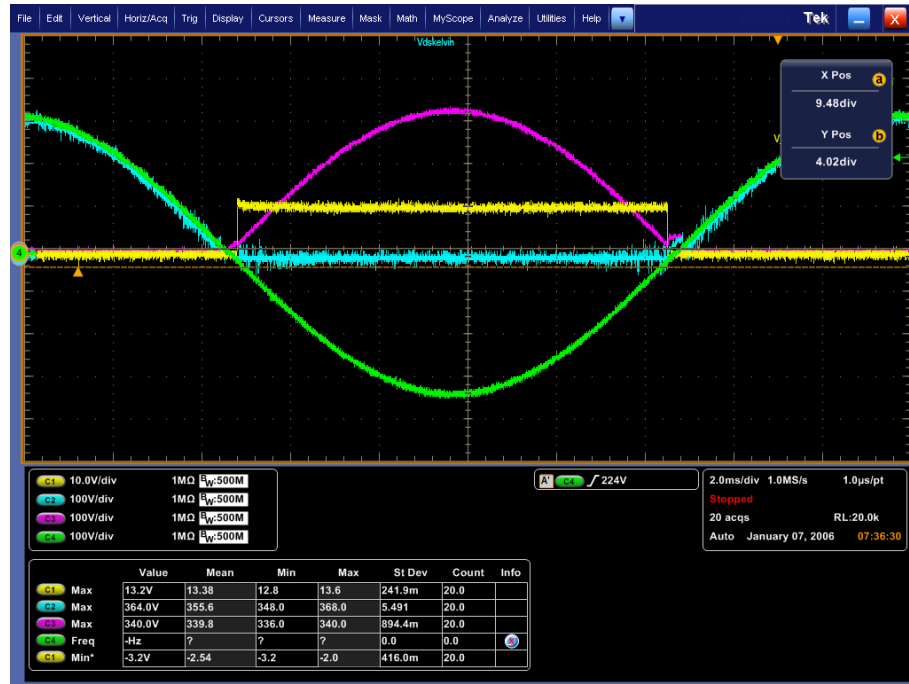


Figure 58: Zoom of waveforms of H-bridge of original setup. Yellow stands for gate-signal, blue and purple for V_{DS} and green for V_{OUT} .

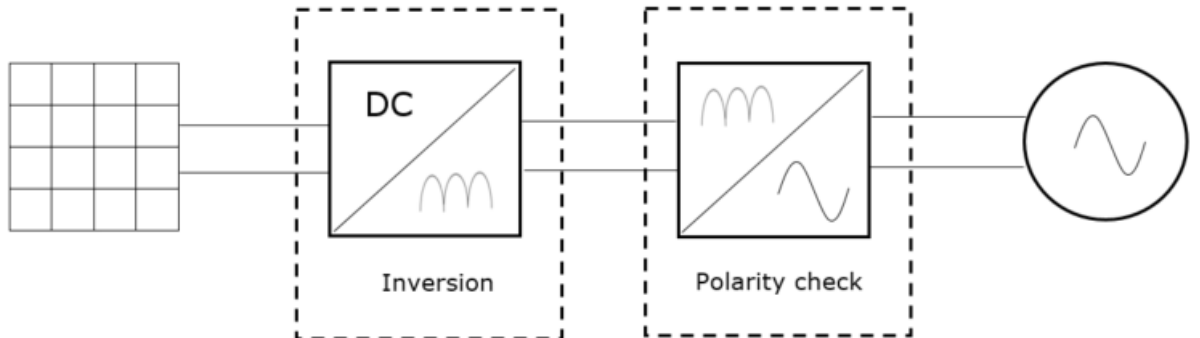


Figure 59: Function states of inverter D.

behind is, that S5 is located immediacy to MOSFETs S2 and S3, and since their temperature increased evidently during the switch replacement, affects this also to the temperature of the S5. Also the lack of soft foam as heat dissipator, impacts to this. S5 was replaced with a more cost-efficient MOSFET, which has higher $R_{DS(ON)}$ than the original one. This logically increases the temperature of the device, as explained in Section 4.1. But, since the initial temperature was lowest of all the switches, this replacement was possible to be done.

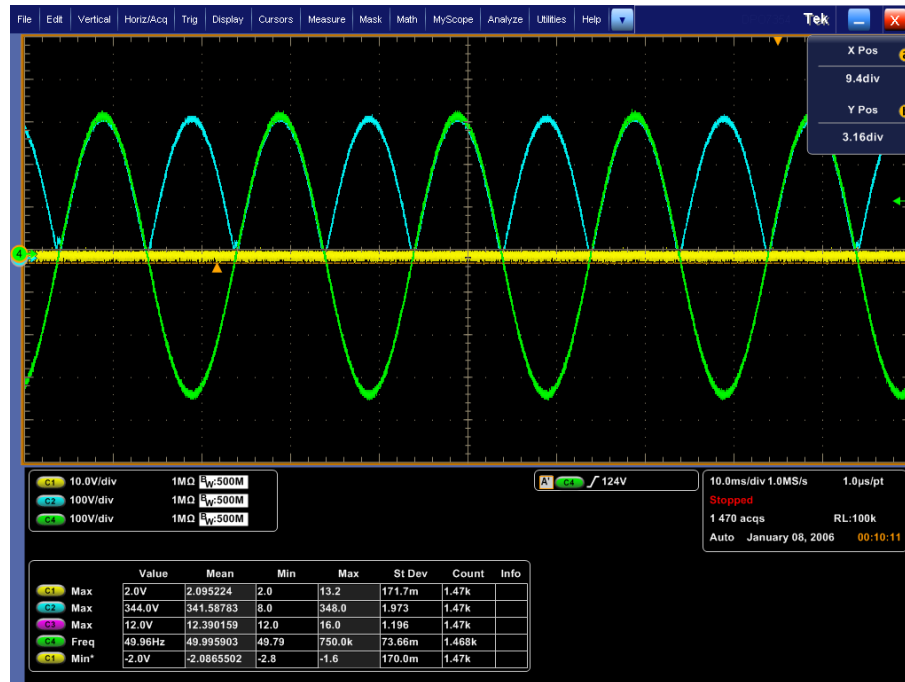


Figure 60: Waveforms of the fifth switch. Yellow stands for gate-signal, blue for V_{DS} and green for V_{OUT} .

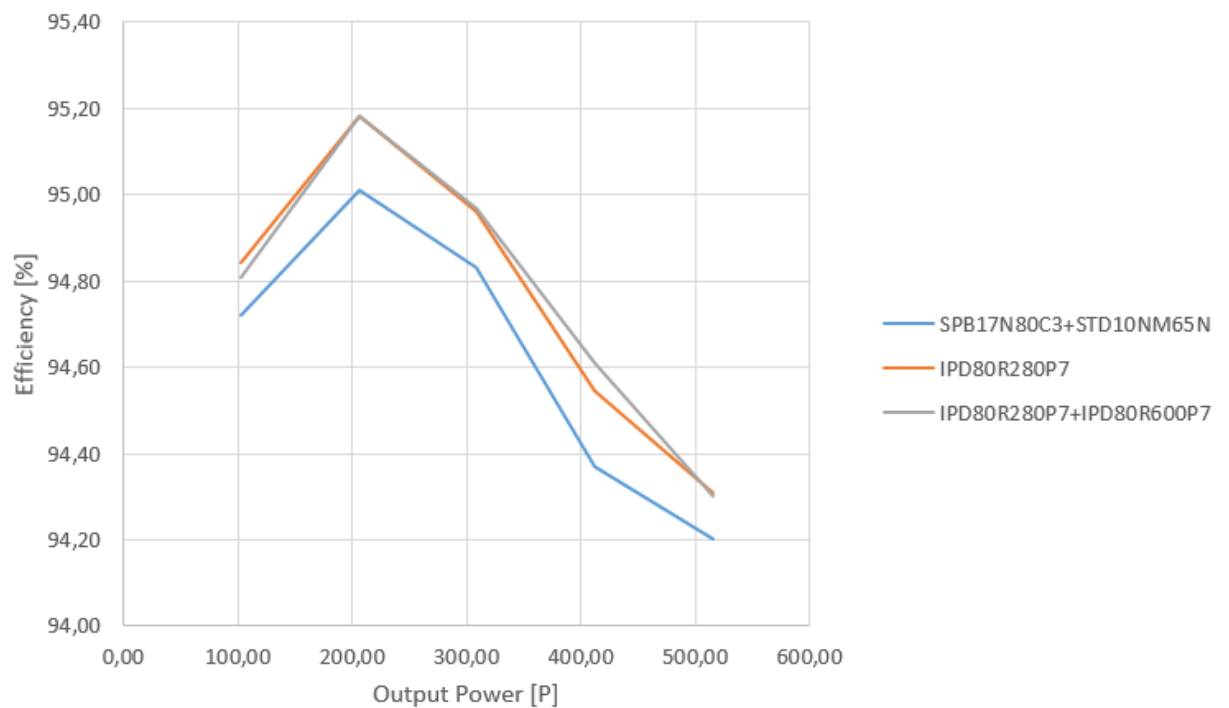


Figure 61: Efficiency curves of inverter D.

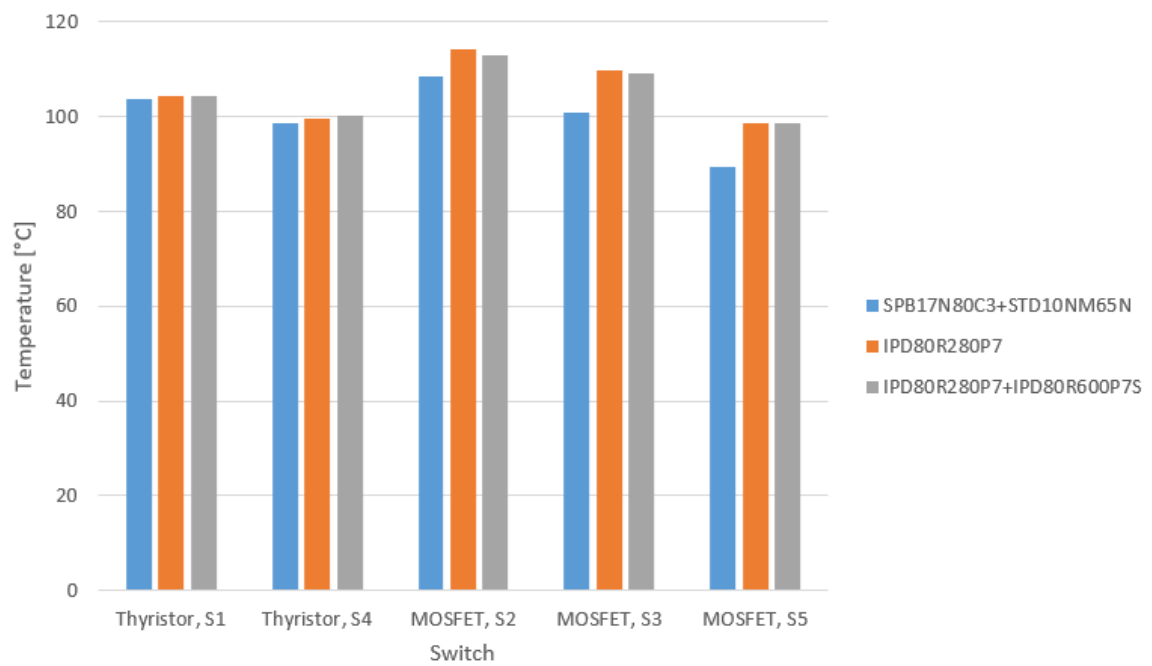


Figure 62: Measured switch temperatures of each switch in the inversion-stage of Inverter D. Also the temperatures of thyristors were measured for interest, even though they were not replaced. Orange pillar stands for the replaced switches in H-bridge and grey one is the replacement of the fifth switch.

5 Conclusion

To stop the global warming, the usage of conventional fossil fuels has to be terminated or at least minimized as good as possible. Solution for this are renewable energy sources, like solar and wind energy. Wind power used to dominate before, but since the cost of solar power has been decreasing rapidly, it is predicted, that solar power will dominate in the future.

Talking about solar power cannot be done without mentioning solar inverters. They invert DC, which is the output of solar panel, to AC, which can be used in local loads and utility grid. Inverter has a significant impact to solar system efficiency and it has also many other functions, than just inversion. Amongst other things, it provides MPPT-tracking, anti-islanding feature and other protection functions, it boosts up the voltage for needed level and it must be low in EMI and THD. Additionally the high-quality inverters participate to reactive power compensation. In the future, it is predicted, that the role of solar inverter will be even more considerable than nowadays.

Solar inverters use semiconductor components as switches. Inverters with smaller power range, like micro inverters, uses normally MOSFETs, since they are suitable for comparatively lower power levels. Whereas inverters with bigger power levels uses either IGBTs or thyristors. MOSFETs allow the highest switching frequency, while thyristors allow the lowest. IGBTs are in the middle of these two.

Grid-tied inverter is an interface between renewable energy source and utility, which makes it currently very interesting from the point of view of development. More accurately, 3-phase low power and 3-phase high power inverters are currently becoming more and more common and interesting for end users. Additionally the panel-integrated inverters, which are already commonly used in micro inverters, are also starting to interest other inverter types.

Currently transformerless topologies interest the market of solar inverters, since compared to topologies with transformers, this implementation is lighter in weight, less bulky and offers better system efficiency. Biggest challenge anyway is the elimination of leakage current, when there is no transformer providing galvanic isolation. Nevertheless in micro inverters, transformers or flyback converters are used. Reverse engineering showed, that using paralleled flyback converters with paralleled low voltage switches is a common way implementate galvanic isolation in micro inverters.

From topology point of view, common way to implement inversion is conventional full-bridge, or also called as H4-topology, and variations of it. These variations are for example H5, H6 and HERIC -topologies, whose idea is to improve the performance. Tear down -part of this thesis showed, that these variations of H4 are common. Also one novel topology, cyclo converter, was found. Its advantage is better efficiency with less components.

Measurements showed, that replacing conventional MOSFETs to efficient super-junction MOSFETs, improves the efficiency. So from the efficiency point of view, replacement is recommended. Also in some cases, even more cost effective decision could be done, concerning the switch selection.

On a scope of this thesis, further research and measurements could be done on the field of transformerless topologies: how much efficiency is gained without a transformer and further, how much would the performance improvement be, when transformerless topologies would be provided with superjunction MOSFETs. Also life-time -improvement of solar inverters could be researched closer and further how for example avoiding the usage of electrolytic capacitors as energy storage and the ambient operating temperature of inverters impact to the life-time.

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